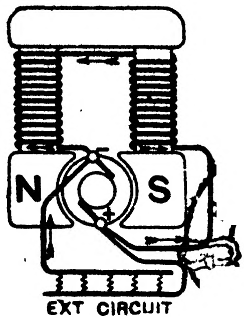

ELECTRIC LIGHTING
AND
POWER DISTRIBUTION

(A MANUAL OF ELECTRICAL ENGINEERING)

VOL. I (9TH EDITION)

" *The day must come when Electricity will be for everyone, as the waters of the rivers and the wind of Heaven. It should not merely be supplied, but lavished, that men may use it at their will, as the air they breathe.*"—EMILE ZOLA.

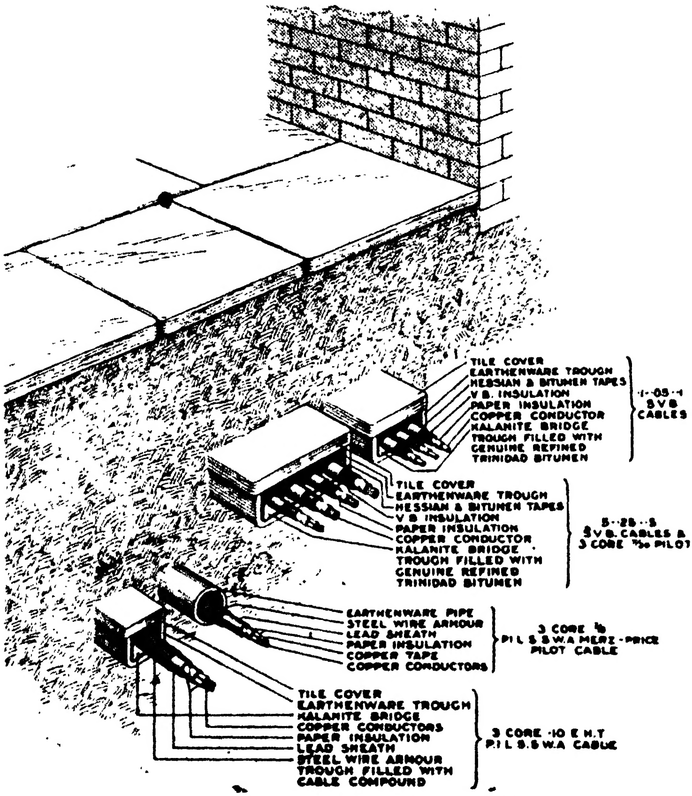

FIG. 270.—UNDERGROUND MAINS.

(Callender Cable and Construction Co., Ltd.)

Low tension three-wire direct current distributor, next the building line.

Low tension direct current feeder, with pilot wire, outside the distributor.

Cable of protective system for transmission cable.

Extra-high-tension alternating current transmission cable.

[Frontispiece

ELECTRIC LIGHTING
AND
POWER DISTRIBUTION

DEALING WITH THE FUNDAMENTAL PRINCIPLES OF ELECTRICITY IN THEIR APPLICATION TO THE ELECTRICAL ENGINEERING INDUSTRIES

BY

W. PERREN MAYCOCK, M.I.E.E.

CONSULTING ELECTRICAL ENGINEER AND LATE TECHNICAL EDITOR TO THE WESTINGHOUSE COMPANIES PUBLISHING DEPARTMENT IN EUROPE

REVISED BY

C. H. YEAMAN

CITY ELECTRICAL ENGINEER, STOKE-ON-TRENT

IN TWO VOLUMES

VOL. I (9TH EDITION)

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PREFACE TO NINTH EDITION

THE two volumes comprising Electric Lighting and Power Distribution are intended to form a textbook for students in the classes at Technical schools, or for home-study by those engaged in the manufacturing, contracting or power supply branches of the electrical industry.

It is hoped that practising engineers, who may not have had a systematic training, will find these volumes of service, particularly Vol. I, which attempts to give reasons for most of the rules guiding practical applications.

Attention is devoted for the most part to principles, rather than to descriptions of plant and apparatus; although the important subject of instruments and their uses is dealt with in considerable detail.

Mr. Maycock wrote the previous editions with the intention of helping the student, who had little beyond a knowledge of arithmetic, to obtain such a sound grasp of fundamentals that his way should be paved to more advanced study. The success which attended the publication of his books may be regarded as proof that the methods followed appealed to a large class of readers, who desired a logical treatment of the subject but expressed in non-mathematical language.

The author's death prevented an earlier revision of Vol. I which now, it is hoped, has been brought up to date without seriously altering the scope of the work. The mode of presentation of facts has been modified as little as possible. Special attention has been given to the requirements of juniors in practical electrical engineering work, and the revision has been based upon the experience gained in training and directing, over a lengthy period of years, many who have taken up such work as a livelihood without much preparatory or professional training. So far as the treatment differs from customary lines, it is intended to give such information as has been sought in their early stages by a number of engineers whose positions are now established in the higher grades of the electrical industry.

In rewriting this book many useful suggestions have been made by Mr. G. E. Gittins and Mr. T. E. Morriss, while Mr. W. E. Swale has kindly assisted by reading the proofs. Thanks are tendered to them, and to Mr. H. Beardmore for preparing many of the new diagrams and figures.

C. H. Y.

CONTENTS

PLATES

NOTES FOR STUDENTS

(*a*) ENGINEERING is the application of science to the needs and customs of everyday modern life. The engineer is the man with educated brain and trained fingers who, within the limitations of our knowledge of science, controls and directs the forces of Nature for the benefit of himself and his kind. Science is organized and systematized knowledge of the workings of Nature. It has been called the great instrument of social change; its end is to promote human happiness, and it is owing to the efforts of those who have advanced science and applied it that, in the last hundred years, the whole material setting of civilized life has altered.

(*b*) Electrical engineering is an art which has grown up from, and out of, certain ascertained or experimental facts. The fundamental statements of these facts are given in a few simple "laws," with which the student must thoroughly familiarize himself, and be able to apply them with any variations or extensions which may be necessary in practice. These "laws" are, to summarize them—

(i) Ohm's law, defining electrical resistance.

(ii) Faraday's law, of electro-chemical action.

(iii) Joule's law, co-relating electrical energy and heat; and a little more complex—

(iv) The laws relating to the interlinking of electric and magnetic circuits.

(v) The inverse square laws applying to charges of electricity and magnetic pole strengths.

(vi) The laws of electro-static and of electro-magnetic induction.

(*c*) These laws are simple when understood, but understanding is only attained by driving them into the mind by explanations of what they mean and, particularly, how they apply in practice. Consequently, the intention has been to use plain and straightforward language. That this is not easy, everyone who is aware of the difficulties with Acts of Parliament will recognize. The sharpest brains of the nation frame our laws; yet their intent, or at least their effect, is doubtful until a decision has been given in the High Courts, and even then the House of Lords may give just the opposite interpretation, if the question be carried so far. To meet this difficulty there is a good deal of repetition in these two volumes; one reader may grasp one explanation, and a second another, but it is believed that it is better to explain too often than to leave a point uncertain.

(*d*) The concentric system is the method whereby a subject is gone over several times. On each stage a little more detailed information is given, and what has already been acquired is used as a foundation for further advanced treatment. This mode of progression has been selected for these two volumes as likely to prove of assistance to readers starting the study of electrical theory and practice.

(e) A course of training or study may be divided into four stages: (i) Preliminary instruction in the first principles of mechanics and physics, electricity, and magnetism. (ii) The elements of applied electricity and the foundations of electrical engineering, somewhat as covered in Vols. I and II of this book. (iii) More advanced work in electrical engineering, for which some of the textbooks mentioned in the list at the end of Vol. II would be necessary. At this stage the subject would naturally be divided into direct current and alternating current work. And lastly, (iv) where the student would begin to specialize and pay particular attention to each branch by itself. Dynamos, alternators, transformers, meters, and cables, for example, would be as exhaustively investigated as time and means permit. Too many students stop short at the second stage. They would be well advised to go farther.

(f) The beginner's difficulty in commencing the subject is due in a great measure to the want of an electrical sense, which has to be cultivated. Electrical quantities and effects require a good deal of careful thinking about before they can be thoroughly understood. One has to draw a kind of mental picture of the conditions and operations of an electrical circuit, and this necessitates a somewhat unusual exercise of the reasoning and imaginative faculties.

(g) One can use the telephone without living through the mental activity of the inventor, but the student of engineering must make an effort to understand at least *why* a telephone can transmit speech. By a cultivation of the imagination the how and why of things can be grasped, but the process must involve some attention to the other branches of science, the relationship of which to engineering is really that of a foundation to a superstructure.

(h) Electricity is of a very intangible nature compared with other "forces." Hence a considerable amount of space has been devoted to explaining simple theory. If the fundamentals are really "understood" it is not difficult to add to such knowledge, while the "whys" which are met with in practical work can be answered and the explanations grasped.

(i) The three avenues to electrical knowledge are: (i) Experimental work in the laboratory, this being specially directed to bringing out facts in such an order that they can be assimilated; (ii) exercises and numerical examples based on and illustrative of principles taught in the lecture room, and (iii) practical experience in the workshop, in the generating station, and on "jobs," so that the applications of the principles may be understood. These three should go forward together. One cannot be taught much, any more than one can be fed much; the process of mental digestion by which one learns is the result of personal application and perseverance. Later on, experience gives one judgment, and then the electrical sense becomes grafted on to one's common sense.

(j) The inventors of the types of electrical machinery in use to-day were engineers who had a sound knowledge of the physical sciences, and although students are rather inclined to begrudge the time spent in seriously "reading up" the more elementary parts of such books as this volume, the best advice which can be given is to grind in the principles thoroughly, and then the practical applications will follow easily.

(*k*) In order to follow many of the explanations in a book of this kind, it is essential that the student should attend a course of practical instruction. No one can expect to learn even the rudiments of electrical engineering from printed matter alone. "The phenomena lie for the most part outside the range of ordinary experience, and laboratory work is important." Useful companions to the present volume are Vols. II and III of the *Electrical Engineering Laboratory Manuals*, "Practical Electricity and Magnetism" and particularly "Electrotechnics," both by Dr. J. Henderson (Longmans, Green, 8s. and 4s. 6d.).

(*l*) Where any technical term, likely to be unknown to the reader, appears, an attempt has been made to define it clearly, and to insert a corresponding reference in the index. Medical and legal textbooks, if bought secondhand, will be found to have copious marginal notes inserted by their past owners, and engineers might well follow such an example.

(*m*) Information on the diverse problems associated with the industrial uses of electricity will not be found in any one book. Different writers each cover sections of the subject, and present their views according to their personal outlook. No one has attempted seriously, and certainly not successfully, to codify electrical knowledge. Hence a habit of reading should be sought and acquired. Notes should be taken of information looked up. Either a simple card system or a loose-leaf book is convenient for this purpose, but the data must be arranged methodically.

(*n*) Battery problems are introduced in the early stages of the subject because they are simpler than those of dynamos. Many important ideas can be gathered from this class, and it is easy to show how many curves, the V for example, which are afterwards met with under more complex conditions, may be derived from data. Nothing should be skipped merely because its application to practice cannot be perceived at a first glance.

(*o*) To keep the volume within reasonable limits, and to prevent its becoming too expensive for the student, certain matters have been relegated to other volumes. Electric bell circuits, for example, will be found in the author's *Electric Wiring, Fittings, Switches and Lamps*. The author's *First Book of Electricity and Magnetism* should be read before proceeding to even a preliminary study of electrical engineering, and if some time has been given to an elementary work on mechanics, so much the better.

(*p*) Considerable space has been given to combinations of resistances and modes of joining them up for different purposes, as well as to pressure-drop and power lost on lines. While it is true that these are often simple deductions from Ohm's law or the applications of that law, so many mistakes are made in everyday engineering work, and students seem to have so much difficulty in deducing for themselves the principles underlying these matters, that more examples than usual are included. They have been grouped so as to illustrate the principles; thus, Kelvin-Varley slides, fault-finders, the Universal shunt and potentiometric resistances have been taken together. It should be noted that these arrangements often crop up in heavy engineering work without the similarity being obvious at first sight.

(*q*) Wherever matters are referred to which are covered by the Home Office or Electricity Commissioners' regulations, reference is made to these because most engineers have to deal with plant and equipment to which these regulations apply. Moreover, these regulations have caused manufacturers to modify their designs so that the whole industry is affected. The Home Office Electrical Inspector's reports frequently draw attention to accidents caused by a want of understanding as to dangers, and how they can be avoided.

(*r*) The student's attention is directed to many of the fundamental notions which underlie the regulations, but all it has been possible to do in the space available is to deal rather summarily with a number of the more difficult questions.

(*s*) When a clear conception of what takes place when a current flows round a circuit (i.e. the physical phenomena which we call "electrical effects") has been gained by the reader, the next thing to which he ought to apply himself is the fixing in his mind of how numerical problems, in relation to these effects, are worked out. For this reason the list of questions at the end of each chapter has been extended. A rather common practice is to glance at a question and, if it looks easy, assume that one is able to go through the processes of arriving at the answer. This is a bad habit to acquire. Serious study connotes the spending of some time systematically in solving examples, with a view to be able at a later date to tackle such problems when they crop up in daily work.

(*t*) Formulae are useful as shortened modes of expressing facts already known. If the student has difficulty in grasping the meaning of a formula he should compare with it the examples which follow and illustrate its use. Then some of the questions relating to the subject should be worked out. For the purpose of proving the correctness of such working, the answers to many of the numerical questions are given, and each of these should be agreed with the student's calculations.

(*u*) Examples and questions are inserted not only as aids to the understanding of the meaning of formulae, but also as an indication of what may be regarded as the knowledge which should be acquired. Some trouble has been taken to include typical questions of the kind which have appeared from time to time during the last thirty or forty years, and which may therefore be regarded as representing what the young electrical engineer should know, according to the opinions of the professors, teachers and practising engineers who have set papers on the subject. More advanced questions will be found in the papers for the examinations of the Associate Membership of the Institution of Electrical Engineers, and the Engineering Degree examinations of London University, as well as in collections such as *Examples in Applied Electricity* (Lamb), (Cambridge University Press, 2s. 6d.). The papers can usually be obtained from examinational bodies for a shilling or two.

(*v*) It is impossible to cover each section of the subject fully, and therefore some questions go beyond the information given. For example, there are some on dimensions of resistances. A great deal of useful information can be gathered by intelligent observation of such plant as may be inspected or handled by the reader, who should keep a notebook and enter therein leading dimensions and particulars of construction of regulating rheostats, load resistances, and other things he comes across. By extending the printed information in this way he will gradually acquire sufficient to answer intelligently any reasonable question which may be put to him. Students going forward to examinations may find the questions suggestive, and cause them to look up matters in some of the books listed in the Appendix.

(*w*) In answering questions, or making reports, give diagrams whenever possible. It is helpful in working problems, or in explaining any occurrence, to make simple sketches representing the circuits or other conditions under consideration, and to note down thereon the particulars given, or "data."

(*x*) For the intelligent perusal of any book which deals at all practically with power distribution by alternating current, there is a minimum mental equipment required. This may be regarded as sound arithmetic, elementary algebra and a smattering of trigonometry. The more that is known of these subjects—the language of quantities—the better.

(*y*) From Vol. I the student can proceed to Vol. II, which is not only a continuation of this book but deals in a more detailed manner with many subjects briefly discussed in the first nine chapters. Thus, matters dealt with in Vol. II have occasionally to be referred to in Vol. I—electrolysis, for example. Practice comes first in order of time with many electrical students, hence they may find explanations of practice in Chapters I to IX. Those who have been through a science course will find in Chapters X to XX applications of the principles they already know. The other special books by the author could then be "read," and by that time the treatises mentioned in the Appendix to Vol. II might be studied profitably.

THE "MEGGER" EARTH-PLATE TESTER.
(*Evershed and Vignoles, Ltd.*)

A phantom photograph of an apparatus designed to overcome the difficulties which are experienced in the measurement of the resistance of earth plates due to electrolytic back e.m.f. and vagabond currents. The instrument is similar to the "Megger" Testing Set and employs the same direct current generator and ohmmeter, but is provided with a special commutator on the armature shaft interposed electrically between the ohmmeter and the soil section of the testing circuit. In this way alternating current is provided for the earth plate while direct current is retained for measurement, thus cancelling out external factors in the soil circuit while permitting the use of the true "moving coils" ohmmeter. (See §225, p. 393, and §231, p. 401.)

ELECTRIC LIGHTING
AND
POWER DISTRIBUTION

CHAPTER I

FORCE, ENERGY, WORK AND POWER

1. FORCE *is that which produces or tends to produce motion or change of motion of matter.* When a body is set in motion it is because a *force* has been applied to it. In order to increase or decrease the motion of a moving body, or to stop it, it is necessary to apply force.

Take, for example, a garden roller upon a smooth level path. To produce motion of the roller it is necessary to apply force, either by pushing or pulling at the handle. When once the roller is in motion, it is comparatively easy to keep it moving. To make it go more quickly, i.e. to change its motion, it is necessary to apply extra force. To stop it suddenly when in motion, i.e. to change its motion from something to nothing, a good deal of force must be exerted.

Force does not always produce motion. Suppose, for example, that a man tries to move a heavily-laden railway truck standing upon a line: though he exert all the force of which he is capable, he will be unable to produce any appreciable movement of the truck. This would be a case of force tending to produce motion. The man cannot move the railway truck, because he is incapable of applying sufficient force to it. A locomotive engine, being able to exert very much more force, could move the truck with ease. As another case in which force tends to but does not produce motion, let us imagine a train of railway trucks standing on a line, with an engine at each end, one pushing one way and one the other. If the engines exert equal forces, their driving wheels will merely slip round on the rails without producing any motion of the train.

2. DIFFERENT KINDS OF FORCE. There are different kinds of force. First of all there is the *force of gravitation,* in virtue of which bodies will fall from a higher to a lower level whenever able. The force which a man exerts when he lifts a heavy body or knocks another man down, is *muscular force.* The force which a horse exerts in drawing a carriage is muscular force. The force which a steam engine exerts is *mechanical force,* due in the first instance to the force of expansion of the steam upon the piston or upon the blades, according as the engine is of the reciprocating or of the turbine class. We have an example of *chemical force* when a mixture of coal-gas and air in a room is ignited, and the resulting explosion blows out the windows.

Electromotive force is a force producing or tending to produce a flow of electricity : and *magnetic force* is a force which produces attraction or repulsion between magnets, or between the fields of current-carrying conductors, or the movement of a current-carrying conductor in a magnetic field.

The motion produced in a train, for instance, i.e. the rate at which it moves along the line, depends upon the force exerted by the engine. Similarly, the rate of "flow of electricity" depends upon the electromotive force: and movements or other actions due to magnetic forces are proportional to the forces.

3. MASS is the quantity of matter in a body : the *weight* of a body is due to the force of gravity acting upon this matter, The greater the quantity of matter in it, the more it will weigh ; so that weight is apparently the same thing as mass ; but this is not so. Weight is due to the force of gravity acting on a body, and gravity is a force tending to pull bodies towards the centre of the Earth. Now this force diminishes as we get farther away from the surface of the Earth, above or below. Thus, the force of gravity acting on a lump of lead, for instance, would be greater at the sea level than at the bottom of a mine, or up in a balloon; or, in other words, the lump would weigh more in the first case than in the second or third. But the *mass* of the lump of lead would not alter; there would be just the same quantity of lead in it in each case. The Earth is not a perfect sphere, the distance from its centre to the surface being greater at the equator than at the poles: consequently, the force of gravity, and therefore the *weight* of a body, is slightly less at the equator than at the poles.

This difference in the weight of bodies at different parts of the Earth, or the difference between the weight as measured in a balloon at a considerable height, and at the Earth's surface, is too small to be readily appreciable, yet a difference does exist. This difference would not be detected at all if the body were weighed in an ordinary balance, however delicate; for the simple reason that just as the pull of gravity on the body in one scale-pan increased or diminished, its pull upon the "weights" in the other scale-pan would increase or diminish in exactly the same proportion; so that balance would be obtained with the same "weights" at any part of the Earth.

By means of a very delicate spring-balance, however, the difference in the pull of gravity on a body at different places may be detected.

Though mass and weight are not the same thing, yet we can measure the mass of a body very conveniently by its weight. Thus, a body weighing 16 grammes has twice the mass or quantity of matter in it as a body weighing 8 grammes, at the same place.

4. UNITS. Whenever anything is measured, such as the mass of a body, or its length, or a duration of time, the result is expressed as a number of units. Thus we say a ton of iron, a yard of wire, a second of time. In these cases, the ton, the yard, and the second are various *units*, of *mass*, *length*, and *time* respectively.

Units are divided into fundamental units and derived units. Thus, a few units are chosen and fixed arbitrarily, and then other units can be expressed in terms of them.

In ordinary everyday life *mass* (or weight) is measured in ozs., lbs., cwts., or tons, etc.; *length* in inches, feet, yards, miles, etc.; and *time* in seconds, minutes, hours, etc. These measures are not good, however, because of the use of units with different names to indicate the same kind of measurement; and also because of the trouble in reducing a value from a larger unit to a smaller, or vice versa. For instance, to reduce a ton step-by-step through the various units—cwts., quarters, and lbs.—to ozs., we should have to multiply by 20, 4, 28, and 16.

There are in general use two systems of units, the British system and the Metric System. The results of many measurements are so well known and are so conveniently expressed in the British system that it is the custom to continue their use. The metric system is, however, so much simpler that in scientific works, or for engineering results obtained by experiments directly based on the recognized laws of science, this is usually adopted.

In the metric or decimal system, derived from the French, there is only one name to remember in connection with each set of measures, and the multiples and sub-multiples of a unit increase or diminish by 10. Thus all calculations are easily and quickly made; the translation of a value to a higher or lower denomination being merely a matter of moving the decimal point to the left or right respectively.*

The word "unit" has a special meaning in electricity supply. It is then an abbreviated form of "Board of Trade unit," i.e. the commercial unit of electrical energy.

5. DECIMAL PREFIXES. The following are the metric or decimal prefixes to units. They may be used with any units, and they increase or diminish the values as follows.

* Consult *The C.G.S. System of Units*, by J. D. Everett (Macmillan. 6s.). Also *Dictionary of Metric Measures* by L. Clark (Spon, 6s. 6d.).

Meg or Mega	=	one million times	.	1,000,000
Myria	=	ten thousand times	.	10,000
Kilo	=	one thousand times	.	1,000
Hekto	=	one hundred times	.	100
Deka	=	ten times	.	10
Unit.				1·
Deci	=	one-tenth	.	0·1
Centi	=	one-hundredth	.	0·01
Milli	=	one-thousandth	.	0·001
Micro	=	one-millionth	.	0·000001

Thus, in common use—

Megohm	=	1 million ohms.	.	(Resistance)
Kilogramme	=	1,000 grammes.	.	(Mass)
Hectare	=	100 ares	.	(Area)
Centimetre	=	·01 metre.	.	(Length)
Milli-ampere	=	·001 ampere.	.	(Current)
Microfarad	=	·000001 farad.	.	(Capacity)

6. METRIC MEASURES. In the table on page 6 are given the metric units of length, mass, volume, and area, and their equivalents in English measure.

In several instances it will be noticed that where the values would require a number of decimal places they have been omitted. This is so for the reason that the fractions are so small as to be negligible.

In dropping from a higher value to a lower and omitting the last figure, when the omitted figure has been 5, 6, 7, 8, or 9, the end figure has been raised. This gives greater accuracy, and is called "rounding off" the significant figures. Thus in the "feet" column, ·899 in the first line becomes ·090 in the second, and ·281 in the fourth. Take another case. In the "pint" column it is required to keep the number of decimal places down to three. If we did not, we should have in the second line 176·0768. But if we cut out the 8 the 6 should be raised to 7; for though this increases the value slightly, it is more correct than if we left the 6. If the figure to be dropped is 0, 1, 2, 3, or 4, no alteration need be made. Some of the values are only given at length to show them exactly; but if in practice we required—say—the number of cubic inches in a hektolitre, it would be quite near enough to take the value as 6103.

LENGTH.

				Inches.	Feet.	Yards.	Miles.
Kilo-metre	=	1000 metres	=	39371·	3280·899	1093·6	·621
Hekto-metre	=	100 metres	=	3937·	328·090	109·36	·062
Deka-metre	=	10 metres	=	393·7	32·809	10·936	·006
Metre	=		=	39·37	3·281	1·094	·001
Deci-metre	=	·1 metre	=	3·937	·328	·109	·000
Centi-metre	=	·01 metre	=	·3937	·033	·010	·000
Milli-metre	=	·001 metre	=	·03937	·003	·001	·000

MASS.

				Grains.	Lbs. (Avoir.).	Cwt.	Tons.
1000 Kilo-grammes	=	1 tonne	=	—	2204·	19·684	·9842
Kilo-gramme	=	1000 grammes	=	15432·	2·205	·020	·0010
Deka-gramme	=	10 grammes	=	154·32	·022	·000	·0000
Gramme	=		=	15·432	·002	·000	·0000
Centi-gramme	=	·01 gramme	=	·15432	·000	·000	·0000
Milli-gramme	=	·001 gramme	=	·015432	·000	·000	·0000

VOLUME.

				Cubic centimetres.	Cubic inches.	Cubic feet.	Pints.	Gallons.
Kilo-litre (Stere)	=	1000 litres (cubic-metre)	=	1,000,000·	61027·051	35·315	1760·768	220·096
Hekto-litre (Deci-stere)	=	100 litres	=	100,000·	6102·705	3·532	176·077	22·009
Litre	=	(A cube, each edge of which = 1 decimetre)	=	1000·	61·024	·035	1·760	·220
Deci-litre	=	·1 litre	=	100·	6·103	·004	·176	·022
Centi-litre	=	·01 litre	=	10·	·610	·000	·018	·002
Milli-litre	=	·001 litre	=	1·	·061	·000	·002	·000

AREA.

				Square Inches.	Square feet.	Square yards.	Square miles.
Square kilometre	=	1,000,000 square metres	=	—	—	1,196,033	·386
Hectare	=	10,000 square metres	=	—	107641·	11960·	·0038
Are	=	100 square metres	=	155003·	1076·4	119·6	·000
Square metre	=	1 centi-are	=	1550·06	10·764	1·196	·000
Square Centimetre	=	0·0001 square metre	=	·155	·001	·000	·000
Square millimetre	=	0·000001 square metre	=	·001	·000	·000	·000

7. THE C.G.S. SYSTEM, or absolute system of units, is founded upon the *fundamental units* of length, mass and time, and is so-called from the initial letters of the units, the centimetre, the gramme and the second respectively. It is called an *absolute system* because the units therein depend only on these three fundamentals, which are presumed to be obtainable anywhere with exactitude. The c.g.s. system, being decimal, has great advantages over the f.p.s. or foot-pound-system, which is the basis of the ordinary British units used in engineering measurements. Another advantage of the c.g.s. system is that the units are directly related. Thus the unit of mass, the gramme, is very nearly the mass of 1 cubic centimetre of water at its greatest density. All the other units of the c.g.s. system, being based upon the three fundamental units, are called derived units, but only a few of these are mentioned herein.

Fundamental Units in C.G.S. System—

Length. The *Centimetre* **(abbreviated** *cm.***)** $= \frac{1}{100}$ **of a metre.**

Mass. The *Gramme* **(abbreviated** *gm.* **or** *grm.***)** $= \frac{1}{1000}$ **of a kilogramme.**

Time. The *Second* **(abbreviated** *sec.* **or** *s.***).**

Derived Mechanical Units—

Area. The *Square Centimetre* **(abbreviated** *sq. cm.***).**

Volume. The *Cubic Centimetre* **(abbreviated** *c.c.***).**

From the first table it will be seen that practically a metre = 3 feet 3 inches and $\frac{3}{8}$ths of an inch. The centimetre is almost exactly 0·4 inch.

8. STANDARDS. Having determined what would be the most convenient unit for a particular quantity, the next step is to settle the best form and material for the standard representing that unit.

An immense amount of extremely careful work was done in the second half of last century in first of all defining the units on the absolute system, and, secondly, in devising standards by means of which there should be no doubt about the concrete realization of each unit.

The standards used in trade, for quantities bought and sold, must have their values settled by law, and those to which all other quantities have to be referred are as follows—

Length. The yard is the distance between lines drawn on two gold plugs inserted into a bronze bar, 38 ins. long and 1 sq. in. cross-section, when the temperature is 62° F. This standard has been reproduced by "authorized copies."

Mass or *Weight*. The pound is the weight of a mass of platinum, the "standard pound" kept under the care of the Board of Trade.

Volume or *Capacity*. The gallon is the standard measure of capacity, and contains 10 lbs. of distilled water, weighed in air when the temperature is 62° F. and the barometer stands at 30 ins.

These standards were fixed by the Weights and Measures Act, 1878. Further particulars relating to them will be found in the Board of Trade Reports on Weights and Measures.

The Metric Standards are preserved by the International Bureau of Weights and Measures, near Paris, and are as follows—

Length. The metre is the length of a rod or bar of platinum termed the "standard metre." Originally the metre was supposed to be one ten millionth of a quadrant of the earth, i.e. of the distance from a pole to the equator, measured along the surface of the globe, but actually it is the length of the standard.

Mass or *Weight*. The kilogramme, embodied in a mass of iridio-platinum.

Volume or *Capacity*. The litre, which is the volume of 1 kilogramme of pure water at a temperature of 4° C. when the barometer stands at 760 mms.

The use of the metric system in this country was authorized by the Weights and Measures Act, 1897. The exact equivalents of the more important metric measures and

Imperial measures as legally authorized for use in trade are as follows—

Metre	= 1·0936143 yds. .	yard	= 0·914399 metre.
Kilometre	= 0·62137 mile. .	mile	= 1·6093 kilometres.
Hectare	= 2·4711 acres. .	square mile	= 259 hectares.
Cubic metre	= 1·307954 c. yds..	cubic yard	= 0·764553 c. metre.
Litre,	= 1·7598 pints. .	gallon	= 4·5459631 litres.
Kilogramme	= 2·2046223 lbs. .	pound	= 0·45359243 kgrm.

It will be found that tables giving the weight of materials per unit of volume differ slightly. This is due to the fact that most materials alter their dimensions with change of temperature, so that the temperature must be stated if exactness be aimed at. For example, water has its greatest density, or weighs the most for a given volume, at about 4° C. This has been taken as the temperature in defining the litre, which strictly is the volume of 1 kilogramme of water at 4° C. The litre is roughly the volume of 1 cubic decimetre, but actually the litre is a little more, 1·000027. The gallon, on the other hand, is the volume of 10 lbs. of water at 62° F. At this temperature water has expanded as compared with 4° C., in the proportion of 1 to 1·001118. In both cases pure or distilled water is assumed, and the pressure of the atmosphere, as measured by barometer, has also to be stated. These differences are so small that they can be ignored in ordinary work, where extreme accuracy is not necessary, but they explain why on picking up "conversion tables" it is found that the figures given do not always *quite* agree, e.g. they range from 62·27 to 62·43 lbs. per cubic ft.

For all practical purposes a cubic millimetre of water weighs a milligramme; and a cubic decimetre, a kilogramme (= a litre). Thus—

1 c.c. = 0·061 cub. in. = 1 gramme (of water).

1 cub. metre = 1·308 cub. yds. = 1 tonne (of water).

1 gallon = 0·1604 cub. ft. = 277·25 cub. ins. = 4·546 litres = 10 lbs. (of water).

1 cub. ft. = 1728 cub. ins. = 28.34 litres = 62·36 lbs. or say 62·4 lbs. (of water).

9. VELOCITY. Motion is change of position. Velocity is the rate of change of position. A body has unit velocity when it moves through unit distance, or length, in unit time. Thus unit velocity is a velocity of one centimetre per second. The word "speed" is generally used to indicate what in scientific language is meant by velocity, but speed is less definite: the term "velocity" including direction as well as rate of change of position.

Momentum may be defined as the *quantity of* motion in a moving body. The momentum of a body is proportional to its mass multiplied by its velocity. To stop, or to change the motion of, a moving body requires the application of force. A rotating fly-wheel with a steel rim would require greater force to stop it than if its rim were made of wood of the same size and shape: its momentum being greater in the first case. Momentum represents energy stored up in a moving body; so that a body with momentum is able to do work when its velocity is reduced.

If a lump of lead and a lump of wood of equal size were let fall from the top of a tower into soft earth, the lead would bury itself to a greater depth than the wood, on account of its greater mass and its consequently greater momentum; even though both had the same velocity. Similarly, a leaden bullet fired from a gun would pass through a greater thickness of wood than a wooden bullet of the same size and fired under similar conditions.

Acceleration is the rate of change of velocity. As a velocity will not change unless a force causes it to do so, the rate at which a velocity changes is a measure of the force acting upon the body whose velocity is altered.

10. THE UNIT OF FORCE is that force which, acting on unit mass for unit time, gives it unit final velocity. In other words, it is that force which, acting on a mass of 1 gramme for 1 second, gives it a final velocity of 1 centimetre per second. This unit is called a *dyne.*

The force of gravity, which is usually denoted by g, and which varies very slightly according to the latitude of the place, is such that all bodies fall to earth with an acceleration of 981 centimetres per sec. per sec. in Great Britain. This is equivalent to 32·2 ft. per sec. per sec.

Thus the force which gravity exerts on a mass of one gramme is 981 dynes; so that 1/981 gramme* gravitates with a force of 1 dyne. Roughly one may say that the weight of 1 milligramme represents a force of 1 dyne.

Since there are 453·6 grammes to the pound, and $g = 981$, 1 lb. gravitates with the force of about 445,000 dynes. Thus, in calculations which are based on absolute units and give the answer in dynes, if we wish to *convert to pounds* (pull or weight) *we divide by* 445,000.

Units of Force, weight or pull—
The absolute unit of force is 1 dyne.
1 gramme, weight or pull = 981 dynes.
1 pound „ „ = 453·6 grammes = 445,000 dynes.

11. **ENERGY** is the capacity for doing work. Thus, energy is expended when work is done. Energy and work are consequently measured in the same units. Heat is a form of energy.

Electrical energy is that particular form of Nature's manifestations which enables electrical work to be done. The conversion of energy is the change from one form to another: thus heat energy can be converted into mechanical energy, as in the steam-turbine; and mechanical energy into electrical energy, as in the dynamo or alternator.

12. **WORK** is done when a force overcomes a resistance. But force exerted does not always overcome the resistance opposed to it, and therefore does not always do work. When a railway truck is pushed along a line, work is done; but a man might exert all the force of which he is capable without doing any work, if he tries to move a heavily-laden railway truck, or to push down a brick wall and fails to do so. A battery with however high an electromotive force does not do work unless it causes a current to flow.

* There are different ways of representing the words "divided by" in symbols. One of these is ÷, another is $\frac{1}{981}$ for the case above, but this is expensive to print. The third is to use the solidus or shilling sign, and set up as 1/981. In each case what is intended to be read is that the figure before the sign, or above the sign, is to be divided by the figure after the sign, or below it.

If a weight be lifted, work is done; the work being directly proportional to the weight, and to the vertical distance through which it is raised. In the f.p.s. system work is measured in *foot-pounds*. Thus 6 foot-pounds of work are done in moving a mass of 1 lb. to a height of 6 ft., or a mass of 2 lbs. to a height of 3 ft. The resistance which is overcome in this case is that offered by the opposing force of gravity. Work does not always consist in lifting weights; for instance, work is done when an engine draws a train, or when an electric motor drives machinery; but the work may still be expressed in foot-pounds.

If a man merely supports a weight without moving it, from an engineering point of view he cannot be said to do work, for by definition, work = force × displacement. From a physiological standpoint however, work is certainly done inside the man's body.

13. THE UNIT OF WORK is the work done in moving a body through unit distance against unit force, or it may be otherwise expressed as the work done in overcoming unit force through unit distance. The c.g.s. unit of work is called the *erg*.

One erg is the work done in moving a body through a distance of 1 centimetre against an opposing force of 1 dyne. Or, what is the same thing, it is the work done when a force of 1 dyne applied to a body moves it a distance of 1 centimetre. If in either case the body were moved through a distance of 10 centimetres, then 10 ergs of work would be done.

A milligramme gravitates with a force of approximately 1 dyne. Therefore we may say that 1 milligramme raised to a height of 1 centimetre represents about 1 erg of work.

The erg is such a small unit that its multiple, the megerg = 1,000,000 ergs, is frequently used. Engineers use a multiple called the kilogrammetre, which represents the work done in raising a weight of 1 kilogramme through a distance of 1 metre. As one gramme gravitates with a force of 981 dynes, it follows that a kilogramme will gravitate with a force of 981,000 dynes. From this, and from the definition of the erg, it will be clear that—

1 kilogrammetre = 981,000,000 ergs = 98·1 megergs.

Kilogrammetre is a shortened form of kilogramme-metre. The unit is sometimes, and more consistently, called the *metre-kilogramme.*

The erg is so small a unit that a multiple of it, the *joule*, is taken as a practical unit. The joule = 10,000,000 ergs.

Work may be done in various ways—*mechanically, chemically, thermally, electrically* or *magnetically*; and it may be reckoned in foot-pounds, kilogrammetres, ergs or joules or in multiples of these.

Electrical energy or work is measured conveniently in a unit—the watt-hour—containing 3,600 joules, and in a still larger unit—the kilowatt-hour—of 1,000 watt-hours, or 3,600,000 joules.

Units of Energy or work—multiples of the erg—

1,000,000 ergs = 1 megerg.
10,000,000 ergs or 10 megergs = 1 joule (or watt-second).
746 joules = 550 foot-pounds.
3,600 joules = 1 watt-hour.
1,000 watt-hours = 1 kilowatt-hour (or Board of Trade Unit).

14. POWER *is the rate of doing work*, and has nothing to do with the actual amount of work done.

Here are two crude but easily understood examples. A boy would take longer to carry a thousand bricks up a ladder on to some scaffolding than would a man. Yet when all the bricks were carried up they would represent the same amount of work done, though the boy might take twice or three times as long to do it as the man. This leaves out of the question the work done by the man and the boy in lifting their own bodies against the force of gravity. The *power or rate-of-working* of the man would be greater than that of the boy. Consider another example. One engine might take 3 hours to draw a certain train from one place to another, while a second might be able to take the same train between the same places in 1 hour. The latter engine would clearly be three times more powerful than the former, because it could do the same amount of work in one-third of the time. When the train had been drawn to its destination, it would represent the same amount of work done, whether it had travelled at the rate of ten miles or thirty miles an hour. In this example both friction and air resistance have been left out of account.

Power is estimated according to the amount of work done in a given time.

In the f.p.s. system of ordinary mechanical measurements—

33,000 ft.-lbs. of work done per minute = 1 h.p., or 1 h.p. = 550 ft.-lbs. per sec.

Another example which may help to make the distinction between work and power quite clear is the case of a motor-car travelling from one place to another. The distance between two places is easily found from a map or guide-book. Call this l in miles. The car will take a certain time to cover the distance, say t in hours. The speed s at which the car travels is stated in miles *per* hour, or $l \div t$. This is a rate, and if the car be fitted with a speedometer, it will indicate the rate in miles per hour by the position of the pointer on the dial. This is one of the few cases outside electrical practice where a *rate* is measured directly.

If the speed be uniform, say 20 miles per hour, and the car continues to travel for 3 hours, then the distance travelled during that time, or l, will be = the rate $\times$ time, or 60 miles.

Now it so happens, perhaps fortunately for electrical engineers, that what is so difficult to measure in most cases, a rate, is particularly easy to measure where electricity is concerned. The speed of walking, for example, can only be found by knowing the distance walked, a length, l, and the time taken to do it, t. The power of an engine is usually found by measuring the work done w in a given time t; this being the time of one complete revolution. The power is then obtained by dividing w by t. The speed of a steamship is obtained by trailing a log astern and measuring the distance l, traversed in the time t, between two readings of the log; when $s = l \div t$ and s is expressed in knots; a knot is a nautical mile *per* hour. This is one of the few cases where a *rate* has a commonly accepted name.

15. ELECTRICAL POWER, however, is from the nature of things more easily measured than electrical energy or work, and the instruments commonly employed give the rate of doing electrical work.

In the above examples, l and t are both quantities; just as £'s and years, or shillings and weeks, are quantities in a scientific sense. But so many £'s-per-annum salary, or so many shillings-per-week wages, are *rates* of pay. The student should consider whether he would prefer a rise of £10 a year, or £20 every two years, and whether the recipients would receive the same total amount of money or not in, say, ten years.

16. THE UNITS OF POWER. Electrical power could be measured in ergs per second, but, because one erg per second is much too small, the practical units are the *watt*, and its multiple, the horse-power, h.p.

1 watt = work done at the rate of 1 joule per sec., or 10 million ergs (megergs) per sec.

1 h.p. = work done at the rate of 33,000 ft.-lbs. per min., or 746 joules per sec., or 76 kilogrammetres per sec.

Units of Power, or rate of doing work—

The absolute unit is 1 erg per sec.

1,000,000 ergs per sec. = 1 megerg per sec.
10,000,000 ergs per sec. = 1 watt (or joule per sec.).
746 watts = 550 ft.-lbs. per sec. = 1 h.p.
1,000 watts = 1⅓ h.p. = 1 kilowatt.
1 watt = 0·7373 ft.-lbs. per sec.
= 0·102 kilogrammetre per sec.
= 1/746 or 0·00134 h.p.

The relation between the horse-power and the watt can be shown thus—

$$
\begin{aligned}
1 \text{ h.p.} &= 550 \text{ ft.-lbs. per sec.} \\
&= 550 \times 30{\cdot}48 = 16{,}764 \text{ cm.-lbs. per sec.} \\
&= 16{,}764 \times 453{\cdot}6 = 7{,}604{,}000 \text{ cm.-grms. per sec.} \\
&= 7{,}604{,}000 \times 981 = 7{,}460{,}000{,}000 \text{ ergs per sec.} \\
&= \frac{7{,}460{,}000{,}000}{10{,}000{,}000} = 746 \text{ joules per sec., or watts.}
\end{aligned}
$$

Knowing the power* of a dynamo in kilowatts, its electrical h.p. may be got approximately by adding one-third to the number of kilowatts. Thus the e.h.p. of a 600 kw. machine is approximately 600 + 200 = 800 e.h.p.

The French h.p. (force de cheval) and German p.s. (pferde-stärke) = 736 watts, = 75 kilogrammetres per sec. = 0·9866 h.p. (English).

17. SUMMARY. It is important that the differences in the meanings of the terms used should be clearly grasped. Matter is that which occupies space. Mass is the quantity of matter in a body. Weight is the attraction of gravity acting on a mass.

Force has to be exerted through a distance for work to be done ; the work being reckoned as the product of the force and the distance through which it has been applied. Energy is the capacity for doing work. Work is done when a force overcomes a resistance. Power is the rate of working, or the rate of expenditure of energy.

A unit is the basis of measurement. Arbitrary units are selected and agreed to by the general body of scientific workers, and some of these are legalized by Act of Parliament and are then used in trade with the force of law behind them. Absolute units depend only on the fundamental units of length, mass and time. Practical units are multiples or sub-multiples of the fundamental units, or units derived from them, and are chosen of convenient magnitudes for everyday use.

Energy may be of different kinds—mechanical, chemical, electrical, magnetic, thermal or luminous. Therefore, by

* The power of an electrical generator is commercially spoken of as its " output."

expending energy, work may be done in each of these ways, and the rate of expenditure in each case is the power. This volume is concerned chiefly with the manifestations accompanying the expenditure of energy in the electrical and magnetic circuits, and the resulting thermal and luminous effects.

Quantitative measurement of these effects requires the aid of reason, and the processes known as arithmetical, geometrical and mathematical. The beginner should develop his thinking faculties by reading one or two of the easier books on the methods of mathematical reasoning.*

As the same quantity of work or power may be measured in different units, there is, and must be, a definite relationship between the units. This has already been explained,

UNITS OF ENERGY

Equals.	Megergs.	Joules.	Ft.-pounds.	Watt-hours.
1 megerg . .	1·	0·1	·0737	·000028
1 joule . .	10·	1·	·7373	·000278
1 foot-pound .	13·562	1·356	1·	·000377
1 kilogrammetre	98·1	9·81	7·233	·00272
1 watt-hour .	36000·	3600·	2654·2	1·0

1 horse-power second = 746 joules = 550 ft.-lbs.
1 horse-power hour = 746 watt-hours = 1,980,000 ft.-lbs.
1 kilowatt-hour = 1,000 watt-hours = 1·341 h.p. hours = 2,654,200 ft.-lbs. = 3,600,000 joules.

UNITS OF POWER

Equals.	Megergs per sec.	Joules per sec. = watts.	Foot-pounds per sec.	Horse-power.
1 megerg per sec. .	1·	0·1	0·0737	·00013
1 watt . .	10·	1·	·7373	·00134
1 ft.-lb. per sec.	13·562	1·356	1·	·00182
1 horse-power	7460·	746·	550·	1·
1 kilowatt .	10,000 ·	1000·	737·3	1·341

* Such, for example, as *Real Mathematics*, by E. G. Beck (Frowde, 15s.).

and the practising engineer must be able to convert, or turn a quantity or rate measured in one set of units into those of another set. For this purpose conversion tables are used. A short and simple sample is given on p. 17.

QUESTIONS

1. What is force ? Does force necessarily produce motion ? If not, why not ?
2. Give examples of various kinds of force and distinguish force from energy.
3. Explain concisely the difference between mass and weight.
4. Say why the weight of a body varies at different altitudes, and at various parts of the earth.
5. If a man supports a weight of 10 lbs. for 17 minutes, does he do any work ? If so, how much ? *Ans.* None.
6. What are the advantages of a decimal system of measures ?
7. Write out the decimal prefixes to units, showing how much they increase or decrease the value of the unit.
8. What is the difference between the c.g.s. and f.p.s. systems of units ? Mention the advantages of the former.
9. State the practical value of the so-called absolute system of units as compared with an arbitrary system.
10. Give the relation between the pound and the gramme, the foot and the metre, the pint and the cubic centimetre.
11. Define the c.g.s. units of area, volume, velocity, force, work, and energy.
12. Why is energy expended in bending or coiling a spring ?
13. Why can a leaden bullet be fired farther than a piece of wood of same shape and size ?
14. Show how and why a weight may be expressed as a force.
15. Explain, with examples, the difference between work and power.
16. *Define:* mass, energy, power, weight, work, and momentum.
17. Give the units of work and power in the British and Metric systems.
18. What are the electrical units of energy and power ?
19. Give the principal equivalents of the practical units of work and power.
20. Write down the terms Work, Force, Power, Quantity, as headings, and then arrange the names of the following units each under its proper heading: Watt, Kilowatt Ampere-hour, Horsepower, Kilowatt-hour, Dyne.
21. Define the terms *watt, joule, Board of Trade unit,* as applied in electric measurement. Distinguish between *energy, work* and *power*. Is a *foot-pound* a unit of work or power ?
22. What are foot-pound, poundal, dyne, and kilogrammetre ? And how are they related ?
23. How many foot-pounds of work will be done in twenty minutes by a motor working at 4 h.p. ?

24. Give the equivalents of the English and French horse-powers in watts, and in ft.-lbs. per min.

25. Explain numerically the relations between the dyne, the erg, the joule, the kilogramme, the British horse-power, and the metric (French) horse-power.

26. Define one kilowatt, and one horse-power. Also, calculate the number of ergs equal to one foot-pound at a place where the acceleration of gravity is 981 cm. per sec. Lastly, calculate the number of ergs per sec. equal to 1 h.p. *Ans.* 13,563,000 and 7,460,000,000.

27. Having given that the length of one foot equals 30·48 cm., that the mass of 1 lb. equals that of 453·6 grammes, and that the acceleration of gravity (at London) is 32·2 ft. per sec., deduce that 1 h.p. is (approximately) equal to 746 watts.

28. How many watts can be obtained from 1 h.p. if the efficiency of conversion be 0·9 ? Show from first principles the connection between the watt and the horse-power. *Ans.* 671·4 watts.

29. Calculate the potential energy in Board of Trade units stored in a reservoir of 100 million gallons capacity, situated 200 ft. above the turbine house. *Ans.* 75,355 units.

30. Write equivalents of the following quantities in the international units based on the centimetre, the gramme and the second—

1 inch.	1 square inch.	1 lb.
1 yard.	1 cubic yard.	1 foot-pound.
g.	1 horse-power-hour.	1 gallon.

31. The average flow of water over a fall 55 ft. high is 1,000 cub. ft. per sec. Calculate the annual value of the electric energy which could be derived from such a fall, at ½d. per unit, supposing that half the power available can be actually utilized. *Ans.* £42,475.

CHAPTER II

QUANTITY, PRESSURE, CURRENT AND RESISTANCE

18. ELECTRICITY. Though, like heat and light, the nature of electricity cannot be explained by comparison with anything tangible, in ordinary electrical engineering work it is convenient to regard it as a sort of invisible fluid. It is frequently spoken of under two conditions or states, either as being "at rest" in the form of a *charge* on a body, or as "flowing" in a *current* through a body. When electricity is at rest on a body, we say that the body is charged "with electricity," or that it has a "charge of electricity" upon it. When electricity flows through a body we speak of it as a "current of electricity."

Whatever electricity may be, we assume for convenience that it is something which can flow through a conductor when a difference of potential, or electrical pressure, or electrical level is set up between the ends of that conductor; or, in other words, when the conductor forms part of a circuit containing a source of electromotive force.

A student with an imaginative mind may find it interesting to read up those explanations of electrical action which are based on the electron theory. An electron is supposed to be the smallest possible particle of negative electricity. Electrons at rest give rise to effects of charges, or static electricity, and when in motion produce the results of a current. While the electron theory has met with general acceptance, it is not essential that it should be introduced into an elementary study of the principles of electrical engineering practice.

19. CURRENT. There are two chief kinds of current, (*a*) direct, or continuous; and (*b*) alternating.

A *direct current* is one which flows round the circuit always in the same direction, while an *alternating* or periodic current is one which changes regularly, or cyclically, in magnitude and direction several hundred times a minute. In the present volume we are chiefly concerned with direct currents.

Direct currents of electricity may be produced either by batteries or dynamos, and alternating currents by alternators. These should be looked upon as appliances for creating or setting up a difference of electrical pressure or level, thereby causing electricity to flow round the circuit.

The "rate" at which electricity flows through conductors, that is the current, is measured in *amperes*. The ampere is one of the three standard units defined by law.

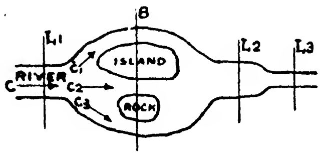


FIG. 1.

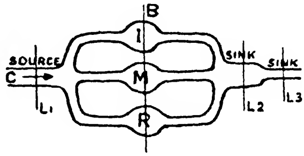


FIG. 2.

It is difficult to measure the rate of flow of water, and it is usually given in gallons *per* hour, or *per* some other time unit, such as "per day." To save trouble, engineers now use the word "cusec" to indicate a flow of 1 cubic ft. *per* sec. It is easy to measure the rate of flow of electricity because many of its effects are proportional to that rate, hence we start with "current."

A current flowing steadily in one direction from a source may divide up into branches, or parallel flows, and reunite again. Then the sum or total of the currents in the branches is equal to the main current. Fig. 1 illustrates this by an analogy. In the river a certain current of water C flows down past the line L_1, which is at right angles to the flow. The main stream splits into three branches, or trifurcates, on meeting with obstructions and passes round these as C_1, C_2 and C_3. These three currents reunite, and at L_2 the stream is the same as at L_1. The rate of flow of water in cusecs is the same at L_1, and L_2, and at B, the branches, or in symbols, $C_1 + C_2 + C_3 = C$. If the river narrows at L_3, the stream will run quicker through a smaller section of river-bed but the cusecs will be the same as at L_1 and L_2.

The electric current C in Fig. 2 flowing through the conductor past L_1 splits into three branch currents in the incandescent lamp I, motor M and radiator R and unites again before L_2. The current at L_1, L_2 and L_3 will be the same, and will equal the sum of the three separate currents through I M and R The three branches are said to be in parallel; they draw from a common " source " and deliver into a common " sink."

20. QUANTITY. Just as a quantity of water may be measured in cubic feet, so a quantity of electricity may be measured in a suitable electrical unit

The unit of quantity of electricity is called the *coulomb*. A coulomb of electricity has no more to do with pressure than a gallon of water has anything to do with pressure or head of water (due to the height of the reservoir). But there is a relation between the coulomb and the ampere, just as there is between a quantity of water and its rate of flow through a pipe. For just as we say that water is flowing through a pipe at the rate of so many cubic feet per second, so we speak of electricity as flowing through a wire at the rate of so many coulombs per second.

1 cubic ft. of water flowing in 1 sec. = 1 cusec.
1 coulomb of electricity flowing in 1 sec. = 1 amp.

When electricity flows through a wire at the rate of one coulomb *per* second, we say that we have a current of one ampere. A rate of flow of—

2 coulombs per sec. = 2 amps.
30 coulombs per min. = 0·5 amp.

When an electric current flows round a circuit it conveys a quantity of electricity, since we have said that electricity in motion is a current.

If a steady direct current be flowing, we can always find out the quantity of electricity, Q, that has passed, i.e. the number of coulombs, by multiplying the current (in amperes) C, into the time of its flow (in seconds) T. Thus—

1 amp. for 30 secs.	=	30 coulombs.
1 amp. for 1 min.	=	60 coulombs.
10 amps. for 1 hr.	=	36,000 coulombs.

or $C, = \frac{Q}{T}$, and $Q = C \times T$

A multiple of the coulomb, the *ampere-hour*, is a unit of quantity employed, for instance, in secondary battery work, and is equal to 3,600 coulombs. Thus the capacity of a battery (i.e. the quantity of electricity it will "give out"), in ampere-hours, is obtained by multiplying together the current in amperes and the time (in hours) during which the battery will force it round the circuit.

A gallon or cubic foot of water can be seen; a coulomb or ampere-hour of electricity cannot. Hence in practice one thinks of a quantity of electricity as current × time, whereas logically the flow of both water and electricity should be spoken of as a rate, i.e. quantity flowing ÷ time of flow. However, it is easier to devise instruments for the measurement of electrical current than for the measurement of electrical quantity.

21. POTENTIAL. The *potential* at any point in a circuit is the electrical pressure or level above or below that of the Earth, which is taken as zero. This is comparable with the measurement of heights or depths from the sea level; or the estimation of temperatures with respect to that of melting ice. Electrical potential above that of the Earth is called *positive* (+); and below that of the Earth, *negative* (–). Even though two points in a circuit be both either at a + or at a – potential, there may be a difference of potential, or a potential difference, between them. Whenever a *potential difference* (p.d.) is created, electricity is set in motion, and may be supposed to flow from the point at high potential to the point at low potential, when the points are connected by a conductor.

The term *pressure* means the difference of electrical potential between any two conductors, or between any part of either conductor and the earth.

Electromotive force, pressure, potential, and difference of potential are measured in volts. The volt is a legal unit, just as the pound in the case of weight. It is the third of the standards defined by law. The term *voltage* is used in practice to mean the number of volts, and therefore is equivalent to pressure.

Everything may roughly be considered to be imbued with a something called electricity, but so long as there is no potential difference, no electrical manifestation will take place. Every electrical circuit may be supposed to be charged with electricity at rest, and at the normal or zero potential; and the effect of introducing a dynamo or battery is to create an *electromotive force* (e.m.f.), and set up a potential difference between the ends of the circuit, and so set the electricity in motion. The dynamo or battery must consequently be looked upon as a device—not for supplying electricity to the circuit, but for pumping or setting into motion the electricity already existing there. The greater the electromotive or electro-pumping force, i.e. the greater the p.d. set up between the ends of the circuit, the faster will the electricity flow round, and therefore the greater will be the current.

22. ACTION OF A BATTERY. A primary or secondary cell may be looked upon as an electric pump, in which the electromotive or "electro-pumping" force is set up by the chemical action going on within the cell. A dynamo is also an electric pump, but its e.m.f. is due to the movement of conductors and magnetic lines-of-force across each other. A dynamo, like a battery, is a pump which works continuously in one direction. An alternator may be likened to a pump which exerts its force first in one direction and then in the other, producing a rapid oscillation of electricity in the circuit, instead of a continuous flow in one direction. When a battery is joined up in an incomplete circuit, it may be likened to a pump, **P** (Fig. 3) whose inlet and outlet are joined by a pipe in which is a stopcock, **S C**, the whole being watertight, and filled with water. If the stopcock be closed, working the pump will produce a difference of pressure on the two sides of the stopcock, the pressure being greater than the normal, say, on the right-hand side, and less than the normal on the left-hand side; the difference of pressure (indicated in the figure by + and − signs) depending upon the "watermotive force" of the

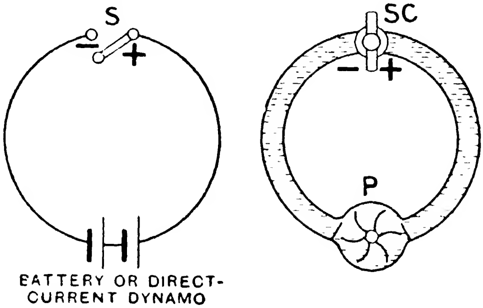


Fig. 3.—Hydraulic Analogue illustrating the Electric Circuit.

pump. If the stopcock be opened, there will be a continuous flow of water round the circuit, the rate of flow depending on the "watermotive force" of the pump, and on the friction in the pipe circuit.

When the battery is on open circuit, i.e. when the switch **S** (which corresponds with **SC** in the right-hand figure) is "off," we may consider that the wires and battery are imbued with electricity evenly distributed. When the e.m.f. is first put in the circuit, this still being open, there is a momentary passage of electricity through the battery thus creating a potential difference between the two ends of the circuit. This potential difference will be equal to the e.m.f. But as the e.m.f. of a battery is small there will be no spark or other discharge across the air-gap at **S**. When, however, the circuit is closed by putting the switch-lever so as to join the parts marked − and +, there will be a continuous flow of electricity round the circuit.

23. CONDUCTANCE AND RESISTANCE. The power of conducting electricity, or permitting it to flow, is called *conductance*, and that of obstructing it, or the opposition to its flow, is called *resistance*. It is all a question of degree, however. Thus conductors have great conductance and little resistance. Semi-conductors have fair conductance and a good deal of resistance; while non-conductors have extremely little conductance and very great resistance.

Conductance and resistance are therefore opposite properties, and are present in everything in opposite degrees so to speak. This may be roughly explained by considering other opposite qualities, such as lightness and heaviness. Thus any given body has both lightness and heaviness. If it is very light, it is not very heavy; while if it is very heavy, it is not very light.

Conductance and resistance being opposite properties of any substance, the quality of a body one way or the other may be considered by talking about either its conductance or its resistance. Sometimes conductance is what most concerns us, but more often it is resistance. Thus, although the extremely good conductance of a copper wire is its chief recommendation, it is usually more convenient for calculating purposes to concern ourselves with its resistance.

24. FALL OF POTENTIAL. There is a certain p.d. set up between the ends of the closed circuit where it is joined to the terminals of the battery in Fig. 3, which p.d. depends upon the e.m.f. of the battery, and on the resistance of the whole circuit. The potential is said to fall from the + end of the circuit to the - end. The total *fall of potential* in volts is equivalent to the p.d. between the ends of the circuit. Thus, if the p.d. be 100 volts, the potential will fall 100 volts from one end of the circuit to the other.

If the circuit conductor be uniform in conductance, the fall of potential will be uniform. Fig. 4 illustrates this by an hydraulic analogy.

The water in the cistern **C**, which is kept at a constant level, has a certain definite head or pressure, in feet. It is allowed to discharge itself through the horizontal pipe P of uniform bore. If a number of vertical open tubes

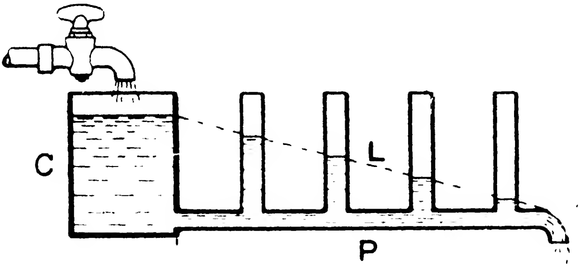


Fig. 4.—Hydraulic Analogue illustrating Fall of Potential.

be fixed at equal distances along this discharge pipe, the water will rise in each tube to a height, depending on the distance of the tube from the cistern: and the height will

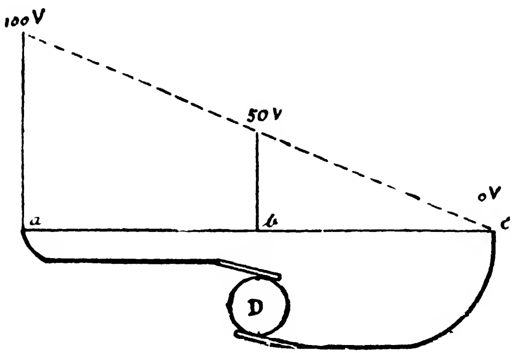


Fig. 5.—Fall of Potential.

denote the water pressure which exists at the various points along the discharge pipe. It will then be noticed that the pressure falls gradually and uniformly from one end to the other, as indicated by the sloping dotted line L.

Compare Fig. 4 with Fig. 5. Here *a* and *c* are the ends of a wire *a b c* of uniform conductance. *a* and *c* are connected respectively with the + and – terminals of a dynamo

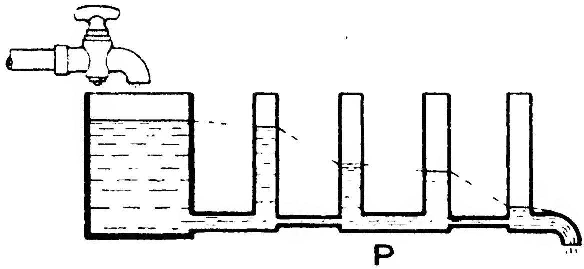


Fig. 6.—Hydraulic Analogue illustrating Fall of Potential.

D, which maintains a p.d. of 100 volts between them. The potential, which is indicated by the height of the

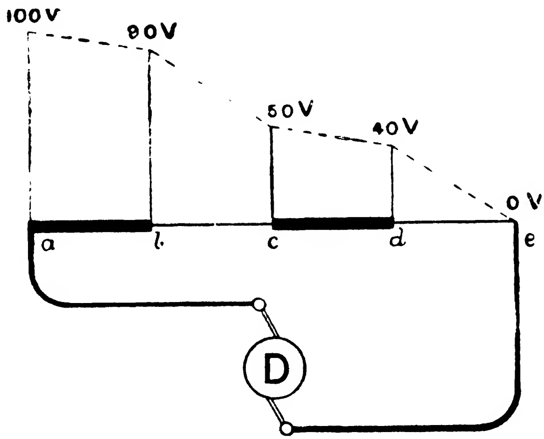


Fig. 7.—Fall of Potential.

vertical lines, will therefore fall uniformly (as indicated by the sloping dotted line) from 100 volts at *a* to zero at *c*. At a point *b*, midway along the wire, the potential would be 50 volts below *a*, and 50 volts above *c*. The *difference of potential* between *a* and *b*, and also between *b* and *c* would be 50 volts.

On the other hand, suppose the circuit be made up of sections having different conductances for a given length. The fall of potential will not be uniform, it being most sudden where the conductance is least and more gradual where the conductance is greatest. This will be understood from the following Figs. 6 and 7. In Fig. 6 the discharge pipe P is not uniform, and the fall of pressure, as indicated by the height of the water in the vertical tubes, is greater in those sections which have the smaller bore and where the friction is greater.

In Fig. 7 there is a drop of, say, 10 volts between *a* and *b* and between *c* and *d*; but the sections *b c* and *d e* of the circuit, having greater resistance or less conductance cause a drop of 40 volts in each case.

The rate of flow of water depends upon the pressure or head of water, and the bore and length of the pipe; and in like manner the rate of flow of electricity along a wire depends upon the electrical pressure at our disposal, and on the resistance of the wire.

25. CURVES OR GRAPHS may be defined as diagrams in which curved or straight lines are employed to represent the relation of certain varying quantities to each other. A "curve" may also have a zigzag form. When one of the two quantities to which the "curve" relates increases or decreases in direct proportion to the other, the "curve" takes the form of a straight line. When one varying quantity increases or decreases gradually with respect to the other varying quantity, but not in direct proportion, the "curve" is truly a curve. When one or both quantities change suddenly, the "curve" is a zigzag line.

Thus a curve may show the relation between the deflections of a galvanometer and the current producing them; or between the magnetizing force acting in a coil of wire and the flux per square centimetre set up in a piece of iron: or between the terminal p.d. and the current developed by a dynamo driven at a constant speed, when resistance of the external circuit is altered, and so on.

A special kind of paper, called squared paper, is employed for setting or "plotting" these curves on; the paper being divided into small squares by equidistant horizontal and vertical lines. (Fig. 8.)

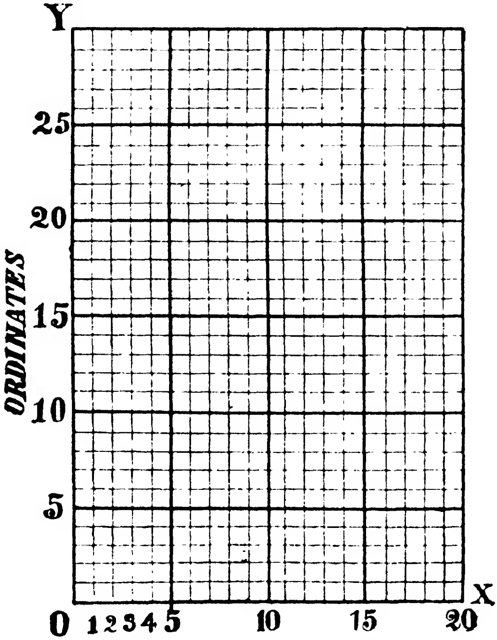


FIG. 8.—SQUARED PAPER.

Distances measures along the horizontal line OX are called *abscissæ*, and those measured along the vertical line OY are termed *Ordinates*. The method of obtaining the curves will be explained in each particular case under notice.

In some cases the zero line of ordinates is a vertical line down the middle of the paper, and the zero line of abscissæ is a horizontal line across the middle of the paper.

Then the conventional signs are + upwards above the horizontal line and - below the same; and + to the right of the vertical line and - to the left of the same. Examples of this method will be found in Chapter VI.

In many of the figures, the smaller squares into which the larger ones are divided up are omitted to render the figures a little clearer; but both large and small squares are shown in some of them.

In Fig. 5, the diagram indicates the fall of potential along a wire of uniform conductance. The distances between the points *a*, *b* and *c* in the diagram represent

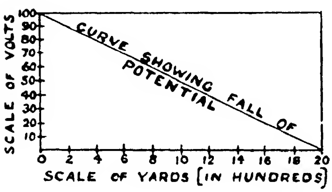


FIG. 9.

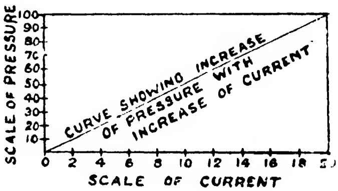


FIG. 10.

lengths, so the diagram can be shown as a "curve" by drawing the sloping dotted line on squared paper with a horizontal scale marked "lengths" as in Fig. 9, where we assume the distance from *a* to *c* to be 2,000 yards.

This curve is a straight line; so is a curve showing the variation of pressure, across a constant resistance inserted in a direct current circuit, with increase of current through it, which would look like Fig. 10.

A curve relating to atmospheric temperature variations from day to day is an irregular zigzag line. In Fig. 7 the fall of potential is indicated in a circuit made up of sections having different conductances for a given length. The curve for these conditions would be like Fig. 11, if we assume conductance *a* to *b* to be equal to 5 times *b* to *c*, and *c* to *d* 3 times *d* to *e*, with *a* to *b* and *c* to *d* equal in conductance, and the four sections equal in length.

In plotting a curve of any kind, it is necessary to make a series of observations which will give points, well separated, on "squared paper," taking a sufficient number to show any peculiarities at any part; and then to draw a line which shall pass through as many of these points as possible. Some of the points may be left untouched on one side and some on the other, this being due to slight errors of observation. Three points are necessary at least to enable a curve to be drawn, and the larger the number of points ascertained the more accurate the curve. Continuing the curve beyond the range of ascertained points

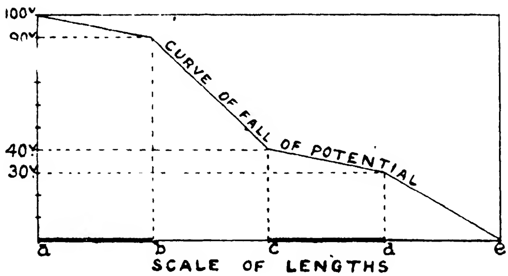


Fig. 11.

is called *extrapolation*, and using the curve to find intermediate values between these points is called *interpolation*.

In some of the curves illustrated later, only the main abscissæ (horizontal) and ordinate (vertical) lines are shown in the diagram, the intermediate ones being left out to render the figure clearer. The squared paper most commonly used is ruled with faint lines every tenth of an inch and main guiding lines every inch, and when it is remembered that such curves as are illustrated were originally drawn on a sheet perhaps 10 ins. square or even larger, it is evident that the intermediate lines must be omitted when the diagram is reduced in size by photographic processes for book illustration.

The value of curves lies in the application of the axiom that "nature does not proceed by jumps"; which means that if, due to a cause, a change takes place, that change as it proceeds will have some definite and ascertainable relationship to the cause. If our observations do not lie on a smooth curve when plotted, then either our observations are erroneous to some extent, or some other cause has been brought into play. A common " other cause " is a change of physical state, such as when ice is changed into water, or water into steam. We all know that warming ice melts it, and warming water makes it hotter until it is vaporized into steam. A curve of the amount of warming, that is of the heat put into the ice or water, compared with its temperature is a straight line practically except at the two points where a change of physical state takes place.

Most people use maps to guide them from place to place. Maps are pictures of what would be seen from an aeroplane looking down upon the earth, using conventional signs to indicate forests, rivers, churches and railways. The " scale " of a map is the proportion a distance measured on the map bears to the distance measured on the ground. But the most useful class of maps have certain red lines upon them called " contour lines." These are lines joining all points of the same elevation or height above a datum or base level. They are therefore closed figures, or endless lines. Water would not flow along the direction of a contour line but at right angles to it, because the slope of the ground is at right angles to a contour line. The nearer contour lines are together the steeper the slope, or the bigger the gradient.

In a similar way we can map out an electric or magnetic field, to show the electric or magnetic height (potential) round a charged body or a magnet. Radiating out there will be lines of electric flow (or electrostatic strain lines) in the one case, and lines of magnetic flow (or flux-lines) in the other. At right angles to these there will be electric or magnetic contour lines, indicating points in the fields where the potential is the same, and these are therefore called *equi-potential* lines.

Graphical representation of quantities, or the use of pictorial means of bringing before the eye magnitudes, or changes in magnitude, is an immense help to the quick and ready appreciation of what is being discussed, and consequently is employed more and more as one gets deeper into the subject of electrical engineering in any of its branches.

26. PRESSURE AND RESISTANCE. Whether electricity will or will not "flow through" a substance at a useful or measurable rate, depends both upon the *pressure* under which it is "flowing," and upon the *resistance* which the substance opposes to its "flow." Lightning is electricity at high pressure, the potential difference between discharge points in the cloud being estimated at as much as 50,000,000 volts, and under such high pressure it is enabled to flow through almost anything. The pressure at which electricity is used in practical work is very much less than that of a lightning flash; and with such low-pressure electricity there are some substances which offer such great resistance to its flow, as to allow exceedingly little to pass through them.

All substances and liquids may be divided into three classes, according to the ease with which electricity can flow through them. Copper, brass, and other metals and alloys, allow electricity to pass through them very easily indeed, in comparison with non-metallic substances; and they are therefore called *conductors*.

Certain liquids, such as the sulphuric acid used in accumulators, the solution of sal-ammoniac in Leclanché cells, the various solutions in electro-plating "baths," and some substances which are neither good conductors nor good insulators are therefore called *semi-conductors*.

Most other non-metallic substances, as well as pure water, certain oils, and air, do not allow electricity to flow through them at all easily, some being practically quite non-conducting. These are consequently termed non-conductors or *insulators*.

27. CONDUCTORS AND INSULATORS. With ordinary working pressures up to, say, a few thousand volts, we may classify substances according to their *order of conductance*. Those at the top of the list offer very little resistance to the flow of electricity, and are therefore good conductors, possessing great conductance.

Although all metals and alloys are very good conductors when compared with liquids and non-metallic bodies, there is considerable difference in their conducting powers when compared with one another.

In the following table a number of metals and alloys are arranged in their order of conductance ; any selected one being inferior in conductance to those above it and superior to those below it. For example, silver is the best conductor of all ; aluminium has less conducting power than copper, gold or silver, but greater conducting power than the metals and alloys below it. Iron is inferior to those metals and to aluminium but is superior to the remainder, except nickel and lead.

The conductive power of copper is very little inferior to that of silver ; and because of this and its relative cheapness, ductility, and freedom from oxidation, it is nearly always used for the cables and wires employed in electrical work.

Aluminium is sometimes used where saving of weight is a consideration, and it is coming into use for overhead lines, for busbars and strap-connections.

As regards the metals, the order given may be taken to be practically correct if they be pure, but conducting power depends on their degree of *purity* and also on their *physical condition*, i.e. whether they are hard-drawn or annealed, and so on.

In the case of alloys the conducting power depends to a great extent upon the proportions of the different metals comprising them, these proportions often varying very much, while a slight variation in the composition makes a great difference in the conducting power. It is an interesting fact that an alloy has less conductance than any one of the metals of which it is composed. Brass, for example, varies very much in composition and its conductance varies accordingly. The order shown in the table, therefore, is only approximately correct.

As we descend the list, the bodies increase in resistance, becoming worse conductors and better insulators. Those at the bottom offer extremely great resistance to the flow of electricity, and are therefore good insulators

Good conductors—

Silver.
Copper.
Silver-copper alloy
Gold.
Aluminium.
Zinc.
Brass.
Platinum.
Phosphor bronze.
Tin.
Iron.
Nickel.
Lead
German silver.
Platinum silver.
Platinum iridium.
Antimony.
Manganin.
Platinoid.
Mercury.
Manganese copper.
Bismuth.

Fair conductors—

Charcoal and coke.
Carbon.
Plumbago.
Lead peroxide.

Semi-conductors—

Dilute acids.
Water (sea).
Metallic ores.
Moist earth.

Fair insulators—

Water (ordinary).
The body.
Linen.
Cotton.
Mahogany.
Pine.
Rosewood.
Walnut.
Teak.

Good insulators—

Marble.
Slate.
Oils.
Porcelain.
Dry leather.
Dry paper.
Silk.
Sealing wax.
Sulphur.
Resin.
Water (pure).
Mica.
Glass (ordinary)
Gutta-percha.
India-rubber.
Celluloid.
Shellac.
Paraffin wax.
Glass (flint).
Ebonite.
Dry air (according to pressure).

There are various other insulators which are not included in the above list, such as asbestos, earthenware, ozokerite, bitumen, etc., as well as a number of artificial materials like ambroin, press-spahn, vulcabeston, micarta, micanite, Chatterton's compound, etc., which have their special uses in electrical work.

Insulators are used for covering cables and wires to prevent leakage of electricity from the conductors, for lining the iron parts of generators, motors and transformers on which covered wire is afterwards wound, and for carrying the naked current-carrying parts of distribution boards and switches. When electricity has to be led from one place to another, or from one thing to another, or is required to circulate round the coils of wire on the magnet of an electro-magnetic device, a more or less complete metallic path must be provided for it, and that path must be surrounded with insulating material along its entire length, so as to prevent the current from either taking a short cut or running away into the earth.

The difference between the best and worst insulators is very great; micanite being about 30,000 times better than slate; resin nearly 3 times better than micanite; and paraffin wax about seven times better than resin. This explains why paraffined wood is so much better than a hardwood itself. But quality and composition make huge differences, and for this reason the values given by various authorities vary widely for a material given the same name.

28. THE UNIT OF RESISTANCE. The ability of a wire to conduct electricity is its conductance. The **mho** is the unit of conductance. The opposition a wire offers to the flow of electricity is its resistance. The **ohm** is the unit of resistance. In this connection it should be noted that "mho" is "ohm" spelt backwards.

The ohm and the mho have a simple relationship to one another, being reciprocal. To get the reciprocal of a number, express it as a vulgar fraction and invert the fraction. Thus the reciprocal of any number n is obtained by dividing it into unity, i.e. the reciprocal of $n = 1/n$. Hence the reciprocal of $0{\cdot}05 = 1/0.05 = 100/5 = 20$. The product of any number by its recipr[illegible] t[illegible] $0{\cdot}05 \times 20 = 1$.

A mho is the reciprocal of an ohm, and an ohm is the reciprocal of a mho. For instance—

Resistance.		*Conductance.*
10 ohms	=	$\frac{1}{10}$ or 0·1 mho.
1 ohm	=	1 mho.
$\frac{1}{10}$ or 0·1 ohm	=	10 ohms.
1 microhm	=	1 megamho.

The ohm is one of the three practical electrical standards defined by law. It is denoted by the Greek letter ω (omega).

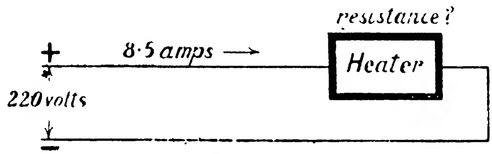


FIG. 12.

Thus, 10 ohms = 10 ω. Very high resistances, such as through insulating materials are denoted in **megohms**, a megohm being 1 million ohms. The Greek symbol Ω (capital omega) stands for megohms, thus, 1 million ohms = 1 megohm = 1 Ω. Very low resistances are expressed in **microhms,** or millionths of an ohm, thus, 0·000001 ω, or 1 millionth of an ohm = 1 microhm.

A conductor has a resistance of 1 ohm when a direct pressure or potential difference of one volt causes a current of 1 amp. to flow through it. Some electric generators set up an alternating pressure, i.e. one which is constantly changing in direction and magnitude. An alternating pressure of 1 volt would give 1 amp. through 1 ohm if it were a simple resistance, like an incandescent lamp. If it were a wire wound round an iron core, then other effects have to be taken into account, which are dealt with in Vol. II. Hence the use of the term "direct pressure" in this paragraph.

The resistance of a circuit is the reciprocal of its onductance. Example, if the conductance of a circuit be ⅔ of a mho, its resistance is 3/2 or 1·5 ohms.

In Fig. 12 an electric heater has a current of 8·5 amps. flowing through it when connected to + and − terminals, having a p.d. of 220 volts. Its resistance is 220 volts ÷ 8·5 amps. or 25·9 ohms.

In Fig. 13 a resistance of 83 ohms has a current of 3 amps. flowing through it. The pressure causing this current to flow is, 3 × 83 = 249 volts.

In Fig. 14 a lamp has a resistance of 25 ohms and it is connected across terminals having a p.d. of 100 volts. The current flowing is 100 ÷ 25 = 4 amps.

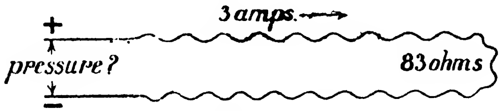


FIG. 13.

In each of these cases a definite thing, heater, resistance or lamp has been taken. As, however, the conductors in each may be of different materials it is necessary to

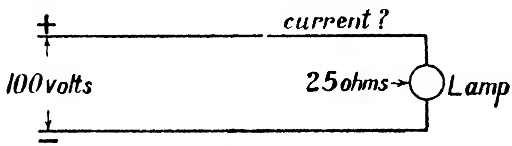


FIG. 14.

find out exactly how much better or worse different *substances* are as conductors.

29. COMPARATIVE CONDUCTANCE. Columns 1 and 2 of the table give the comparative conductances and the comparative resistances of various metals and alloys. Silver, being the best conductor, is denoted by 100, the values for the other metals being proportionately less. The comparative resistance of silver is taken as 1, the other metals having proportionately higher values.

Water appears three times in the first list of substances. It differs enormously in resistance according to purity. Thus the most carefully distilled water ever prepared (*a*) has a thousand times the resistance of tap, or ordinary, water as supplied for domestic purposes.

	Col. 1. (Approximate.) Comparative Conductance.	*Col. 2.* Comparative Resistance.	*Col. 3.* Conductivity. (Specific Conductance.) At 0° C. (approx.) (Megamhos.)	*Col. 4.* Resistivity. (Specific Resistance.) At 0° C. (approx.) (Microhms.)
Silver (annealed)	100	1	·6702	1·492
Copper (annealed)	95·03	1·052	·6370	1·570
Copper (hard drawn)	93·08	1·075	·6238	1·603
Silver (hard drawn)	92·10	1·086	·6172	1·620
Gold (annealed)	73·10	1·368	·4900	2·041
Gold (hard drawn)	71·83	1·392	·4815	2·077
Aluminium (annealed)	51·65	1·936	·3461	2·889
Zinc (pressed)	26·73	3·741	·1792	5·581
Platinum	16·61	6·022	·1113	8·982
Iron (pure)	15·48	6·463	·1037	9·638
Gold Silver (Au. 67, Ag. 33)	13·84	7·223	·0927	10·78
Nickel (annealed)	12·07	8·285	·0809	12·36
Tin (pressed)	11·39	8·779	·0763	13·10
Iron (telegraph wire)	9·94	10·05	·0666	15·00
Lead (pressed)	7·66	13·05	·0513	19·47
German Silver (Cu. 60, Zn. 26, Ni. 14) (hard or annealed)	7·187	13·92	·0481	20·76
Platinum Iridium (Pt. 90, Ir. 10)	6·898	14·50	·0462	21·63
Platinum Silver (Pt. 67, Ag. 33)	6·168	16·21	·0413	24·19
Platinoid (Cu. 59, Zn. 25·5, Ni. 14, W. 1·5)	4·591	21·78	·0307	32·5
Antimony	4·238	23·60	·0248	35·21
Manganin (Cu. 84, Ni. 12, Mn. 4)	3·141	31·84	·0210	47·5
Constantin	2·985	33·6	·02	50·0
Mercury	1·581	63·23	·0106	94·34
Bismuth (pressed)	1·147	87·20	·00768	130·1
Carbon (for arc lamps)	·0373	2681	·00025	(about) 4,000
,, (graphite)	·006721	14880	·000045	(average) 22,200
Selenium	·000000002487	40,210 millions	·0000000000166	60,000 millions

Cu. = Cuprum	=	Copper.
Zn. = Zincum	=	Zinc.
Ni.	=	Nickel.
Pt.	=	Platinum.
Ag. = Argentum	=	Silver.
Ir.	=	Iridium.
W. = Wolfram	=	Tungsten.
Au. = Aurum	=	Gold

Rough description.	Comparative conductance.	Resistance per cm. cube.
(*a*) Pure distilled water	1	5 Ω
(*b*) Commercial ,,	25	0·2 Ω
(*c*) Condensate water in central stations	50	0·1 Ω
(*d*) Tap water from lake	200	25,000 ohms
(*e*) ,, ,, wells	500	10,000 ,,
(*f*) ,, ,, river	1,250	4000 ,,
(*g*) Canal water	12,500	400 ,,
(*h*) Sea water	250,000	20 ,,

A common figure taken for what may be regarded as pure water is ½ megohm per cm. cube at normal temperatures.

An application of the foregoing facts gives a simple means of testing leaky condenser tubes on board ship. A small flow of the feed water from the hot well is taken through a closed glass vessel in which there are electrodes in circuit with a current indicator and a battery. So long as the water is fresh the current is negligible. When salt begins to appear the pointer of the indicator shows on the dial the increasing saltness of the water.

Chemical solutions have greater resistivity than carbon and less than hardwood. For example, the solution of sulphuric acid, at the density used in secondary batteries, has over half a million microhms per inch cube. The average value of carbon is 2,800, so that such a solution is about 200 times greater.

30. CONDUCTIVITY. In column 1 of the table are given the comparative conductances of materials commonly employed, but this is not precise enough. It is equivalent to saying that iron is denser than water, and cork less dense, because iron sinks and cork floats. To enable us to make calculations about water and iron and cork we weigh, say, 1 cubic in. of each and then know how much denser iron is than water, and water than cork. These figures are called specific densities.

In a similar way, if we desire to express accurately the relative conductances of copper and iron and mercury, the conductance of a cubic inch of each would be measured. This would give the specific conductance of the respective materials. Specific quantities are usually designated by the ending ****-ity. Thus, specific conductance is called *conductivity*. In column 3 of the table there is set out against the various metals and alloys their conductivity.

The conductivity, or *specific conductance*, of a substance is the conductance between opposite faces of a unit volume of the substance. The unit volume taken may be 1 in. cube, or 1 cm. cube. In the foregoing table the conductivity is given in megamhos per centimetre cube. In English measure the values would be given as conductivity in mhos or megamhos per inch cube.

31. RESISTIVITY. The resistivity, or *specific resistance*, of a substance is the resistance measured between opposite faces of a unit volume of the substance. In the table, the resistivity is given in microhms per centimetre cube. In English measure the values would be given as resistivity in ohms or microhms per inch cube.

Suppose we take an inch cube of copper, such as is represented in Fig. 15, and measure the resistance between the whole of the top face *a* and the whole of the bottom face *b*, it would be found to be something between 0·00000063 and 0·0000007 of an ohm, say 0·00000066 ohm, or **two-thirds of a microhm.** This is the average resistivity of copper, expressed in English measure, and is a most useful figure to remember. The conductivity of such copper is the reciprocal of its resistivity, and would therefore be 1/0·00000066, or 1,500,000 mhos, or 1½ megamhos. Resistivity values enable the resistance of conductors to be readily calculated and compared.

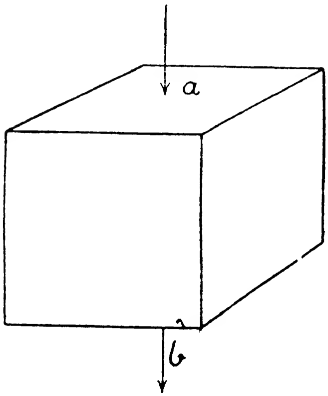


FIG. 15.

32. SERIES CONNECTION. If one has a 1 in. length of, say, copper bar and places it end on to another piece also 1 in. long, the two will measure 2 ins. in length. It would reasonably be assumed that if one had a copper cube having a resistivity of ⅔ of a microhm and placed a second end on to the first, the resistance of the combination would be four-thirds or 1·33 of a microhm. Experiment shows that this assumption is correct.

In this method of connecting the cubes, the current flows through first one and then the other, and they are then said to be joined in series. Any number may be joined end on, so that the same current flows through each ; they are then all in series connection.

The resistance of a combination or set of resistances, taken as a group or whole, is the joint resistance. *To get the joint resistance of two or more wires, or circuits in series, add their resistances together.*

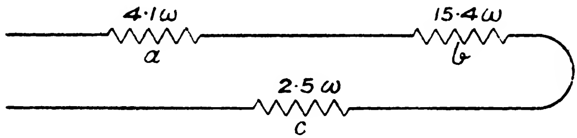
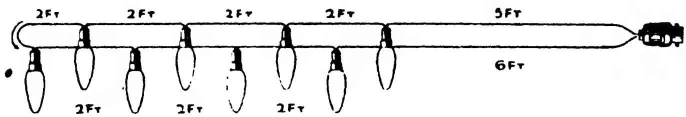


Fig. 16.

Ex. In Fig. 16 the three resistances *a*, *b* and *c* are connected together by copper wires whose resistance is supposed to be negligible, or so small compared with the resistances that they are of no account in discussing the question. If their separate resistances are as indicated, their joint or combined resistance will be 4·1 + 15·4 + 2·5 = 22 ohms.



(*General Electric Co., Ltd.*)

Fig. 17.

The joint or combined resistance of any number of *equal* resistances, arranged in series, is equal to *n* times the resistance of any one of them ; *n* being the number of resistances.

Fig. 17 shows a number of small lamps connected in series, as used for Christmas tree decorations. Lamps run in this way must be adjusted or selected so that each takes the same current. Arc lamps for street lighting used to be run in this way : 30 or so being in series, each taking 50 volts and requiring 1,500 on the circuit ; the current through the circuit being, say, 10 amperes.

33. CURRENT IN A SERIES CIRCUIT. To send a current through resistance requires pressure. We cannot have a circuit without more or less resistance, and we cannot get a current through the resistance of the circuit without pressure.

In a simple series circuit, whatever it may be, the current will be equal at all points—or in all parts—of the circuit. If a circuit consist of a wire of uniform material and size,

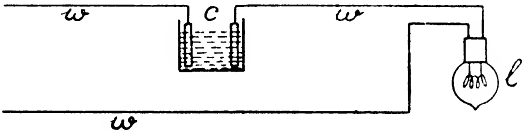


FIG. 18.

it will be readily understood that the current is the same all the way round.

When the circuit is not uniform, the current is still the same throughout. In Fig. 18, for example, the resistance is mainly in the lamp *l* and the cell *c*, as the copper connecting wires *w* have comparatively little resistance; but the current is the same whether we consider the wires, the acidulated water in the cell, or the filament of the lamp.

34. DIVISION OF PRESSURE. The division of a steady direct pressure in the parts of a series circuit is in direct proportion to the resistance of these parts.

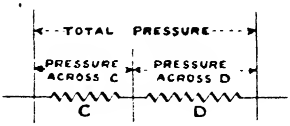


FIG. 19.

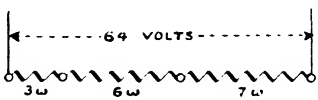


FIG. 20.

In Fig. 19 the pressure divides between the two parts C and D. If C and D be equal in resistance the pressure will divide equally between them. If C has greater resistance than D, more pressure will be taken across C than across D. If C has twice as much resistance as D, twice as much pressure will exist across C as across D; in other words, two thirds of the total pressure will exist across C, and one-third across D.

Ex. (Fig. 20.) Three wires in series have resistances respectively of 3, 6 and 7 ohms. How would a pressure of 64 volts divide between them ?

The joint resistance is $3 + 6 + 7 = 16$ ohms.

Across the 3 ohms there would be	$\frac{3}{16}$ths	of 64	=	12 volts.
,, 6 ,, ,,	$\frac{6}{16}$ths	,,	=	24 ,,
,, 7 ,, ,,	$\frac{7}{16}$ths	,,	=	28 ,,
	Total pressure	.		64 volts.

35. PARALLEL CONNECTION. There are two simple ways in which such cubes of copper as in Fig. 15 may be connected one with the other. They may be put end on, in which case they are in series. The other way is to place them side by side, in the same manner as bridges may be placed across a river, each bridge connecting the two banks. Each bridge then conducts its own traffic across the stream, and the more bridges there are the greater amount of traffic that can be carried across in a given time.

If we place two cubes of copper side by side we increase the area in which the current can flow and the conductance will be doubled. If each cube has a conductivity of $1\frac{1}{2}$ megamhos then the conductance of the combination will be 3 megamhos. In this method of connecting the cubes the current divides between the two cubes, and they are then said to be connected in parallel.

In the case of conductors, if one end of each be joined together, and the other end of each also together, they are in parallel. Any number may be joined up with one set of ends joined together and the other set of ends also joined together, they are then all in parallel connection.

36. JOINT CONDUCTANCE. If a circuit comprises a wire a, and another wire b is connected in parallel with it, an additional path will be provided for the current and the total conductance will be $a + b$. Also if a third wire c be connected in parallel with the others, the total or combined conductance will be $a + b + c$. If these are all equal, the goodness of the circuit as a pathway for current is twice as great when a and b are in parallel, and when c is added, the current will have three equal paths instead of one.

Ex. (a). The joint conductance of the parallelled conductances in Fig. 21 = 0·244 + 0·065 + 0·4 = 0·709 mho.

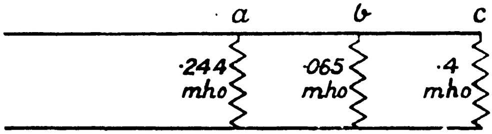


FIG. 21.

Just as the joint resistance of conductors joined in series is the sum of their respective resistances, so *the joint conductance of conductors joined in parallel is the sum of their respective conductances.*

In practice it is more common to talk about the resistance of a conductor than of its conductance. But one can be changed to the other simply by taking its reciprocal, so that no difficulty need arise.

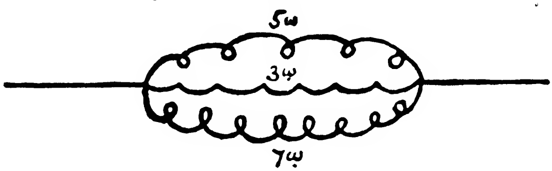


FIG. 22.

Ex. (b). Find the joint resistance of three wires in parallel, their separate resistances being respectively 5, 3 and 7 ohms (Fig. 22).

$$\text{Joint conductance} = \frac{1}{5} + \frac{1}{3} + \frac{1}{7} = \frac{71}{105} \text{ mho.}$$

$$\text{Joint resistance} = \frac{105}{71} \text{ ohm} = 1{\cdot}48\ \omega.$$

The joint resistance of any number of equal resistances arranged in parallel, is equal to $\frac{1}{n}$*th the resistance of one of them ; n being the number of resistances.*

Ex. (*c*). (Fig. 23). Supposing that there be 25 incandescent lamps arranged in parallel, and that each lamp has a *resistance* of 600ω, their joint resistance will be $\frac{600}{25} = 24\omega$.

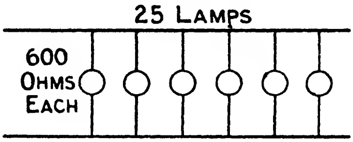


FIG. 23.

Ex. (*d*), In Fig. 24 thirty-six lamps are connected to a distributing board, DB, and they each have a resistance of 200 ohms when alight The supply is at a pressure of 50 volts. The joint resistance of the group will be 200 ÷ 36 or 5·555 ohms, and the total current, therefore, will be 50 (volts) ÷ 5·555 (ohms) or 9 amps.

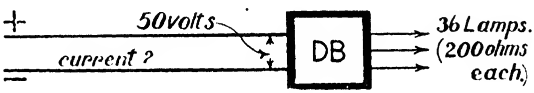


FIG. 24.

37. DIVISION OF CURRENT. In the series connection the current is the same throughout the circuit, and the pressure is divided between the parts according to their resistances. In the parallel connection, the pressure is

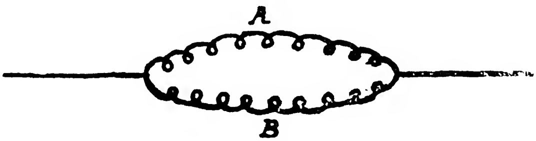


FIG. 25.

the same across each of the parts, and the current divides between these parts or branches.

When a steady direct current divides to flow through two or more parallel branches in a circuit, the fraction of the total current in each branch will be directly proportional to its relative conductance. The greater part of the current will take the easier path, and the lesser part will follow the more difficult path.

In Fig. 25 the current divides between the two branches *A* and *B*. If *A* and *B* be equal in conductance, the current will divide equally between them. If *A* has greater conductance than *B*, more current will flow through *A* than through *B*. If *A* has twice as much conductance as *B*,

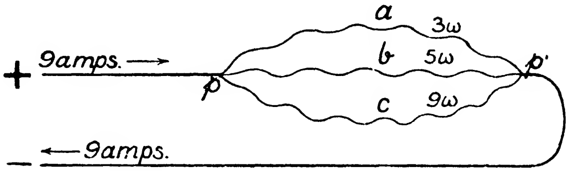


Fig. 26.

twice as much current will go through *A* as through *B*; in other words, two-thirds of the main current will go through *A*, and one-third through *B*.

In Fig. 26, for example, 9 amps. is the main or total current, and at *p* it has to split up between three parallel conductors reuniting at *p'*. If *a*, *b* and *c* were of equal conductance the current would divide equally between

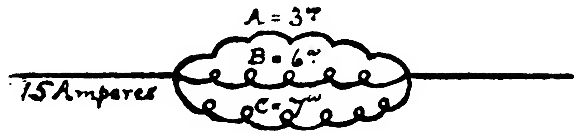


Fig. 27.

them, 3 amps. flowing through each. With branch circuits as marked, the 3 ω would carry 4·65 amps., the 5 ω 2·80 amps., and the 9 ω 1·55 amps. The total current of 9 amps. is proportional to the total conductance, and each branch current is proportional to the conductance of that branch; or, in other words, that the p.d. across *p* and *p* being common to *a*, *b* and *c*, the current through each branch × its conductance = that p.d.

The division of a steady direct current in the branches of *a divided circuit is in direct proportion to the conductances of the branches.*

Ex. Find the conductances of the branches in Fig. 27, and the currents will be in proportion.

Branch.	Resistance.	Conductance.	Current.
A	3	$\frac{1}{3}$ or 0·33 mho	$\frac{\cdot 33}{\cdot 64} \times 15 = 7{\cdot}7$ amps.
B	6	$\frac{1}{6}$ or 0·17 ,,	$\frac{\cdot 17}{\cdot 64} \times 15 = 4{\cdot}0$,,
C	7	$\frac{1}{7}$ or 0·14 ,,	$\frac{\cdot 14}{\cdot 64} \times 15 = 3{\cdot}3$,,
	Total Conductance	= 0·64 ,,	Total current 15·0 ,,

38. RESISTANCE AND CONDUCTANCE being reciprocal to one another it follows that there is another way of putting the statements already made if one wants to

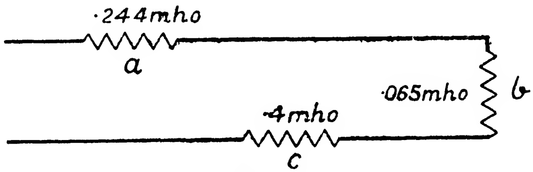


Fig. 28.

add conductances in series or resistánces in parallel. The simple way when dealing with conductances in series is to convert each into resistance, and then add. This may be given in the form of a rule that the joint or combined conductance of two or more conductances connected in series is equal to the reciprocal of the sum of their reciprocals.

In Fig. 28 are the same three wires or coils as in Fig. 16, but their conductance values are given instead of their resistances. The reciprocals of the conductances give the same figures as in Fig. 16; the sum is 22 ohms and the reciprocal of this is the joint conductance = 0·0455 mho.

The simple way when dealing with resistances in parallel is to convert each into conductance, and then add. This may be given in the form of a rule that the joint or combined resistance of two or more resistances connected in parallel is equal to the reciprocal of the sum of their respective conductances.

In Fig. 29 the coils or wires which were in series in Fig. 16 are shown connected in parallel. The reciprocals of the resistances are added, i.e. $1/4{\cdot}1 + 1/15{\cdot}4 + 1/2{\cdot}5 = 0{\cdot}244 + 0{\cdot}065 + 0{\cdot}4 = 0{\cdot}709$ mho, and the joint resistance $= 1/0{\cdot}709 = 1{\cdot}41$ ohms.

It is unnecessary to memorize lengthy algebraic extensions of the foregoing principles if the reciprocal idea be once mastered and remembered.

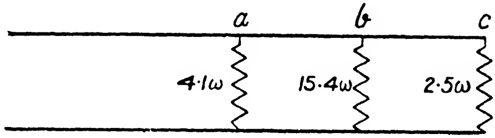


Fig. 29.

39. RESISTANCE. The resistance of an electrical appliance, or piece of apparatus, is often marked upon it, or it can be ascertained by measurement. Electrical conductors usually take the form of wires, that is long lengths of metal pulled through draw-plates so that they have a circular section. Many of the calculations which have to be made require a knowledge of the resistance of wires, either wound on spools or bobbins, as parts of appliances, or stretched out and supported in some way as the lead and return conductors to form a circuit.

The resistance of a wire depends upon four things—

(*a*) On its **length.**
(*b*) On its cross-sectional **area.**
(*c*) On the **material** of which it is made.
(*d*) On its **temperature,** or physical state.

(*a*) *The resistance of a conductor is proportional to its length.* With a given cross-sectional area, the greater the length, the greater must be the resistance of the wire. Thus if 20 yds. of a certain gauge of wire have a resistance of

1 ω, the resistance of a mile of the same wire will be $1760 \div 20 = 88\ \omega$

(*b*) *The resistance of a conductor is inversely proportional to its cross-sectional area.* With a given length, the greater the cross-section the less will be the resistance. A wire of a certain material and length, having a cross-section of 0·008 sq. cm. will offer twice as much resistance as a wire of the same length and material, having a cross-section of 0·016 sq. cm.

(*c*) *The resistance of a conductor is proportional to the resistivity of its material.* If we take wires of different materials but otherwise the same, the different resistances could be calculated from the table of comparative resistances already given, presuming the resistance of one of the wires was known.

Thus, supposing we have wires of silver, copper, iron and German silver, if the resistance of the silver wire were 5ω, then the resistance of the other wires would be respectively: copper, $5{\cdot}3\omega$; iron, $32{\cdot}3\omega$; German silver, $69{\cdot}6\omega$.

For instance, in the case of the silver and iron wires—

resis. iron : resis. silver : : Comp. resis. iron : Comp. resis. silver.

or x : 5ω : : 6·463 : 1

i.e. $x = 5 \times 6{\cdot}463 = 32{\cdot}3\omega$.

The resistance R of a wire, at any fixed temperature, is directly proportional to its length l, inversely proportional to its cross-sectional area a, and directly proportional to the resistivity ρ of the material of which it is made,

$$\text{or } R = \frac{l}{a}\rho$$

where $\rho =$ Greek letter rho, used for resistivity values. If l be expressed in inches, a must be in square inches, and ρ in ohms per inch cube If l be expressed in centimetres a must be in square centimetres, and ρ in ohms per centimetre cube

The student should be careful to guard against the common mistake of multiplying length and area together to get the volume, and dividing by resistivity Resistivity values should be stated to be "per inch cube" and not per cubic inch to avoid this confusion.

The resistance of an inch cube of copper is $\frac{2}{3}$ of a microhm. Two such cases placed in series would have a joint resistance of $1\frac{1}{3}$ microhms and measure 2 ins. long, so that length varying with resistance follows from the rule for resistance in series. Two such cubes placed in parallel would have a joint resistance of $\frac{1}{3}$ of a microhm, so that area varying inversely with resistance follows from the rule for conductances in parallel.

The resistivity of copper in metric measure will be $\frac{2{\cdot}54^2}{2{\cdot}54} \times 0{\cdot}66 = \frac{6{\cdot}452 \times 2}{2{\cdot}54 \times 3} = 1{\cdot}69$ microhms per cm. cube. In the foregoing resistivity table, the values are given in microhms, so that they must be divided by 1,000,000 to give ρ in ohms.

Ex. (*a*). If the resistance of 110 yds. of a single No. 18 wire is 1·45 ohms, what is the resistance of 1 mile of 7/18 cable, neglecting the effect of stranding ?

R increases with l, = 1760/110 or 16 times the length.

R decreases with a, = 1/7 or 7 times the area.

$$\therefore \frac{16}{7} \times 1{\cdot}45 = 3{\cdot}314 \text{ ohms.}$$

Ex. (*b*). Find resistance of 1,000 yds. of copper bar, 1 sq. in. in section.

$$R = \frac{l}{a} \times \rho = \frac{36 \times 1000}{1} \times 0{\cdot}000000666 = 36 \times {\cdot}000666 = 0{\cdot}024 \text{ ohm.}$$

This is the figure given in the British standard specification as the resistance of a solid conductor of standard annealed copper, 1,000 yds. in length, and of a uniform cross-sectional area of 1 sq. in. at 60° F. Exactly it is 0·0240079 ohm.

Ex. (*c*). A copper conductor has a resistance of 1·045 ohms, and its sectional area is 0·04 sq. in. *Find length.*

$$l = \frac{R\,a}{\rho} = \frac{1{\cdot}045 \times 0{\cdot}04}{0{\cdot}00000066} = 63{,}360 \text{ ins.} = 1 \text{ mile length.}$$

Ex. (*d*). One mile of copper wire has a resistance of 0·3052 ohms. *Find area.*

$$a = \frac{l \times \rho}{R} = \frac{(1760 \times 36) \times 0{\cdot}00000066}{0{\cdot}3052} = 0{\cdot}137 \text{ sq. in. area.}$$

Area is proportional to weight per unit length. Thus if for a given length we double the weight of metal in a conductor, the area is doubled and the resistance reduced to half.

Ex. (*e*). Find the resistance x of 1 mile of a conductor weighing 150 lbs. if 1 yd. weighs 1 lb. and r is 0·00174 ohm.

R for one mile $= 1760 \times 0{\cdot}00174\ \omega. = 1760$ lbs. in weight.

x for 1 mile $= \frac{1760}{150} \times (1760 \times 0{\cdot}00174) = 35{\cdot}93$ ohms.

Resistivities are not obtained in practice by measuring the resistance between the opposite faces of a cube of the material, but by testing carefully the resistance of a length l, of a wire, made from the material, whose area is a.

Then $\rho = R \times a/l$.

Ex. (*f*). 28 ft. of No. 20 copper wire, having a diameter of 0·036 in., has a resistance of 0·231 ohm. Find ρ.

$$= \frac{Ra}{l} = 0{\cdot}231 \times \frac{(0{\cdot}7854 \times 0{\cdot}036 \times 0{\cdot}036)}{28 \times 12} = \frac{0{\cdot}231 \times 0{\cdot}001018}{336} =$$

0·0000007 or 0·7 microhm per in. cube.

Ex. (*g*). 97 cms. of No. 20 manganin wire, having an area of 0·0062 sq. cm., have a resistance of 0·627 ohm. *Find* ρ

$$\frac{R \text{ in ohms} \times \text{area in sq. cms.}}{\text{length in cms.}} = \frac{0{\cdot}627 \times 0{\cdot}0062}{97} = 0{\cdot}00004 \text{ ohm}$$

or 40 microhms per cm. cube.

Resistivities are given in text-books for a material of specified composition in a certain state, i.e. hard-drawn, annealed, etc., and at a stated temperature.

40. AREAS OF WIRES. Cross-sectional area and diameter are not directly proportional to each other. A wire with twice the diameter of another will have four times the area. For example, in Fig. 30 the wire w has

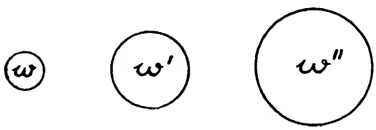


FIG. 30.

a diameter of 0·2 in., and the w' a diameter of 0·4 in., while w'' has 0·6 in. The sectional area is proportional to the square of the diameter—

Diameters	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	1	$1\frac{1}{2}$	2	3	4
Areas	$\frac{1}{16}$	$\frac{1}{9}$	$\frac{1}{4}$	$\frac{4}{9}$	1	$1\frac{1}{2}^2$	2^2	3^2	4^2.
or	0·0625	0·111	0·25	0·445	1	2·25	4	9	16

The area of a circle having a diameter d is equal to

$$\pi r^2 = \frac{\pi}{4} d^2 = 0{\cdot}7854 \times d \times d.$$

The cross-section of area of an ordinary round wire can be found if *r* or *d* be given. Here π (Greek pi) is the ratio of the circumference of any circle to its diameter, for in any circle, circumference $\div$ diameter $= 3{\cdot}1416 = \pi$.

π being a constant quantity, it follows that the areas of circular wires are proportional to the squares of their diameters; and also that the diameters are proportional to the square roots of the areas. Thus if *d* be multiplied by 2, 3 or 4, the original area will be multiplied by 4, 9 or 16. If the diameter be reduced to one half, one third or one-quarter, the original area will be reduced to $\frac{1}{4}$th, $\frac{1}{9}$th or $\frac{1}{16}$th respectively. Conversely, if *a* be multiplied by 2, 3 or 4, the original diameter will be multiplied by $\sqrt{2}$, $\sqrt{3}$ or $\sqrt{4}$ respectively.

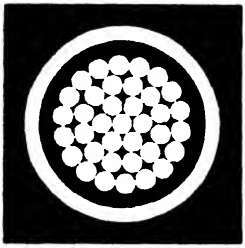


FIG. 31.

A cable is made up of a number of strands of wire and its conducting or effective area is equal to the sum of the cross-sections of the several strands. In Fig. 31 the conductor consists of 37 strands and assuming the figure is the actual size of the cable, the strands are about No. 12 gauge. The circular white band represents the lead or other outer sheathing or covering of the cable, and the black in between is the insulating material, or dielectric. The outer black square has nothing to do with the cable, but is merely inserted to make the illustration stand out.

Ex. (*a*). The resistance of one mile of copper wire 0·064 in. diameter is—

$$R = \frac{63{,}360 \times 0{\cdot}00000066}{0{\cdot}7854 \times 0{\cdot}064 \times 0{\cdot}064} = \frac{0{\cdot}04182}{0{\cdot}003217} = 13 \text{ ohms.}$$

Ex. (*b*). Find diameter of a copper wire, of which 1,000 yds. has a resistance of 3·025 ohms.

$$a = \frac{1000 \times 36}{3{\cdot}025} \times 0{\cdot}00000066 = 0{\cdot}007854 \text{ sq. in.}$$

$$\therefore \frac{0{\cdot}007854}{{\cdot}7854} = 0{\cdot}01 = d^2 \text{ and diameter} = 0{\cdot}1 \text{ in.}$$

See also example (*f*) on p. 53, where ρ has to be found from data of length, diameter, and resistance.

41. COILS AND SPOOLS. The same weight of metal may be disposed in different ways. Suppose we have a square plate, as in (*a*), it will have a certain resistance. If we want a longer conductor, it can be cut across forming two half-plates *b* and *c*. Each of these will have twice the resistance of *a*, consequently as they are in series the

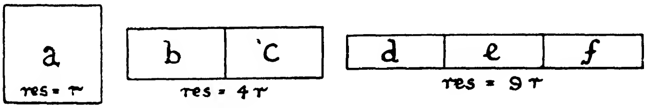


FIG. 32.

total resistance will be four times that of *a*. If cut into three strips, each one-third the width of *a*, the total resistance will be nine times that of *a*.

A similar case is where a constant or fixed volume has to be filled with wire. Neglecting space taken by insulation, to double the number of turns on a spool or bobbin means reducing the cross-sectional area to half, then each turn has twice the previous resistance, but as there are double the number of turns the total resistance is four times what it was before.

Hence with fixed weight of metal the resistance varies as the square of the length, and with constant volume of a bobbin the resistance varies as the square of the number of turns. The latter statement has its application in the winding of electro-magnets, and in the resistance of instruments of the ammeter and voltmeter type.

42. EFFECT OF HEAT ON RESISTANCE. **(d)** *The resistance of a conductor depends on its temperature.* Metals increase in resistance on heating, regaining their original resistance on reaching their former temperature. Thus a given piece of copper wire with a certain resistance at ordinary temperatures will have a slightly greater resistance if, from any cause such as the passage of a relatively strong current through it, its temperature increases. The amount of increase with temperature varies according to the metal or alloy of which a wire is made. This increase of resistance with temperature occurs to a greater extent with pure metals than with alloys. The resistance of certain alloys, such as eureka and constantan. does not increase very much when their temperature increases. These alloys were invented for the purpose of providing practically unvarying resistances for insertion in electric circuits for certain purposes. Alloys are used. therefore, where it is desired that a change in temperature should not cause a large variation in resistance.

There is one notable exception to the general rule. Manganin (an alloy of copper, manganese and nickel) rises in resistance slightly up to 40° C., and falls in resistance again at higher temperatures. It is thus said to have, first a positive, and then a negative *temperature coefficient.* For most purposes, however, its variability of resistance with temperature may be neglected.

Liquids which are capable of electrolysis lessen in resistance when heated. Mercury, which conducts but is not split up or electrolyzed, increases in resistance just as solid metals do.

Copper, on reaching a temperature at which it changes from the solid to the liquid state, suddenly doubles its resistance.

The insulating powers, i.e. the resistances, of india-rubber, gutta-percha, glass, porcelain, ebonite and other good insulators, decrease enormously with a rise of temperature.

The resistance of carbon and metal lamps is no at constant quality but varies with their temperature ; and as their temperature varies with the current through them, it follows that the resistance of a lamp depends on the current traversing it.

The resistance of a carbon filament lamp *decreases* as the current through it increases, whereas the resistance of a metal filament lamp *increases* as the current increases. In fact the hot resistance of a carbon filament lamp is about half its cold resistance, while the hot resistance of a metal lamp is something like six to nine times its cold resistance. By hot resistance is meant the resistance of the filament where it is heated to the usual temperature for giving light.

The above-described different behaviour of carbon and metal lamps explains the fact that the latter are much less affected than the former—so far as the heating of the filament is concerned—when the pressure on the lamp terminals varies one way or the other. In other words, an increase or decrease of pressure will not affect the temperature of metal filaments, and therefore the light emitted, so much as that of carbon filaments.

With metal filament lamps, and also with some heating apparatus in which the heat is generated in wires of high resistance, the resistance is much less and the current consequently much greater at the moment of switching-on than when the filament or the wires have had time to heat up, though the latter process only takes a second or so. This explains why fuses sometimes give way when apparently there is no cause for their doing so. If a number of metal lamps, or a large heater (whose wires have considerably less resistance when cold than when hot), be switched off *immediately* after being switched on, the sparking at the switch contacts will be much more noticeable than if the switching-off had taken place after the lamps or heater had attained full heat.

43. TEMPERATURE COEFFICIENT. The variation in the resistance of 1 ohm of a conductor at any given temperature when its temperature is raised by 1° is known as the *temperature coefficient* of resistance of the material of which that conductor is made, and is generally denoted by α (Greek alpha).

Experiments, made with extreme care, have shown that if a 1 ohm, at 0° C., coil of annealed copper wire, of the kind employed in winding magnets and used for electric conductors be tested at different temperatures, its resistance will be—

Temperature.	Ohms.	Temperature.	Ohms.
0° C.	1·000000	15·0° C.	1·063975
1° C.	1·004265	15·6° C. = 60°F.	1·066321
2° C.	1·008530	16·0° C.	1·068240
3° C.	1·012795	16·1° C. = 61° F.	1·068709
4° C.	1·017060	20·0° C.	1·085300
5° C.	1·021325	21·0° C.	1·089565

A copper wire having a resistance of 1 ohm at 0° C. would have a resistance of 1·004265 ohms at 1° C. The original resistance being 1 ohm, the increase in resistance is 0·004265 for rise of temperature of 1° C. a for copper at 0° C. is therefore 0·004265. A coil of 100 ohms would increase to 100·4265 ohms, which is in the same proportion, i.e. each ohm of the hundred ohms would increase by 0·004265. *For 2° C. rise, the increase in the 1 ohm coil* would be 2 × 0·004265, or 0·008530 ; and for the 100 ohm coil 100 × 2 × 0·004265, or 0·8530 ohm.

From this definition it follows, that if a resistance of 1 ohm at 0° C. be increased in temperature by t° C., the change in resistance is $a\ t$, and the new resistance is $(1 + a\ t)$. Further, if a conductor has a resistance of R_o at 0° C., and has its temperature increased by t° C., its new resistance R_t is : $R_t = R_o\ (1 + a\ t)$.

From this it follows that the temperature coefficient a of the metal of which a wire is composed is the increase in resistance, $R_t - R_o$, per ohm of original resistance, R_o per C°., or in symbols—

$$R_t = R_o\ (1 + a\ t)$$

$$R_t \div R_o = 1 + a\ t$$

$$\text{and } \frac{R_t}{R_o} - 1 = \frac{R_t - R_o}{R_o} = a\ t$$

$$\text{and if } t = 1°\text{C., then } \frac{R_t - R_o}{R_o} = a$$

The increase in resistance per ohm is the same for each degree rise in temperature, or the change follows what is termed " a straight line law." The temperature coefficient may, however, be given for the change in resistance for one degree alteration in temperature, taking some other base, or starting point than 0° C. The figure representing the temperature coefficient will then be a different one because the *constant* increase in resistance per degree becomes a smaller proportion of the whole resistance. This is similar to giving a fixed increase in wages. If an office boy, receiving 10s. per week, and a clerk £2 10s. per week, each get a " rise " of 1s. per week, it is 10 per cent increase on the wages of the office boy but only 2 per cent. on the salary of the clerk.

The 1 ohm coil will have a resistance at 20° C. of—

$$1 \times [1 + (0{\cdot}004265 \times 20)] = 1{\cdot}085300 \text{ ohms},$$

and at 21° C. its resistance will be—

$$1 \times [1 + (0{\cdot}004265 \times 21)] = 1{\cdot}089565 \text{ ohms}.$$

Each ohm of the resistance has risen from 1 ohm at 20° C. to—

$$\frac{1{\cdot}089565}{1{\cdot}085300} = 1{\cdot}00393 \text{ ohms at } 21^\circ \text{ C}.$$

The increase is 1·00393 – 1·00000, or 0·00393 ohm for a rise of 1° C., starting at 20° C., therefore we say that " at a temperature of 20° C. the temperature coefficient of copper is 0·00393 per degree Centigrade." This is the international standard, taken as a normal value for annealed copper.

Neither 0° C. nor 20° C. are average temperatures in this country, and as copper conductors have the same temperature as the air before they are connected to an electrical circuit, a *standard temperature* of 60° F. (or 15·55° C.) has been adopted. An increase of 1° F. raises the temperature to 61° F. (or 16·11° C.).

At 60° F. (or 15·55° C.) the resistance of the coil which was 1 ohm at 0° C. will be—

$$1 \times (1 + 0{\cdot}004265 \times 15{\cdot}55) = 1{\cdot}066321 \text{ ohms},$$

and at 61° F. (or 16·11° C.) it will be—

$$1 \times (1 + 0{\cdot}004265 \times 16{\cdot}11) = 1{\cdot}068709 \text{ ohms}.$$

Each ohm of the resistance has risen from 1 ohm at 60° F. to—

$$\frac{1{\cdot}068709}{1{\cdot}066321} = 1{\cdot}0022 \text{ ohms at } 61^\circ \text{ F}.$$

The increase is 0·0022, wherefore we say that "at a temperature of 60° F., the temperature coefficient of annealed copper is 0·0022 per degree F." This, or its accurate statement 0·0022221, is the coefficient adopted as a British standard figure for conductors. Unfortunately, the Fahrenheit scale of temperature has been retained.

At 15° C. the resistance of the coil would be 1·063975 ohms, and at 16° C., 1·068240 ohms. The rise per ohm would be

$$\frac{1{\cdot}068240}{1{\cdot}063975} = 1{\cdot}00400,$$

hence, the temperature coefficient is 0·004 per °C., for ordinary air temperatures as a base. This is the figure it is advisable to memorize. A degree Fahrenheit is $\frac{5}{9}$ths of a Centigrade degree, hence for 1° F., the figure becomes $5 \times 0{\cdot}004 \div 9 = 0{\cdot}002222$ as stated above.

It is easy to remember that a copper coil increases its resistance about 1 per cent for every $2\frac{1}{2}$ degrees rise in temperature Centigrade. This is equivalent to the temperature coefficient given above of 0·004, which is the same thing as saying it is 0·4 per cent.

The temperature coefficient at any one temperature is related to the temperature coefficient at any other temperature in inverse proportion to the resistance at which the coefficient is taken. Thus at 0° C., $a = \frac{R_1 - R_0}{R_0}$ where R_1 is the resistance at 1° C. and R_0 that at 0° C. At some higher temperature t° the resistance will have increased to $R_o \times (1 + a\,t)$ and the coefficient at that temperature for 1° C. rise will be expressed by the proportion a now bears to that greater resistance or

$$a \text{ (at } t^\circ \text{ C.)} = \frac{a \text{ at } 0^\circ \text{ C.}}{1 + a\,t} = \frac{1}{\frac{1}{a} + t}$$

In the case of copper a for 0° C. = 0·004265, thus 1/0·004265 = 234·5, and the formula becomes $\frac{1}{234{\cdot}5 + t}$

Ex. (*a*). Find the temperature coefficient for copper at 60° F. This = 15·5° C., hence a (at 15·5° C.) = $\frac{1}{234{\cdot}5 + 15{\cdot}5} = \frac{1}{250}$ = 0·004, which agrees with the figure already given above.

The *average* values between 0° C. and 100° C. of the temperature coefficient of resistance for the principal metals and alloys are—

Copper, 0·0043; Aluminium, 0·0044; Iron, 0·00625; German Silver, 0·000273; Manganin, 0·000001.

Ex. (*b*). A coil of copper wire is immersed in melting ice (0° C.) and a length of one ohm is cut off and put into boiling water: what will its resistance become?

$$R_t = 1\,[1 + (0{\cdot}004 \times 100)] = 1 + 0{\cdot}4 = 1{\cdot}4 \text{ ohms.}$$

Ex. (*c*). A coil of copper wire of 2,401 ohms at 60° F. is heated up to 96° F. How much will its resistance have risen? Use formula in (*b*) and coefficient given in text of 0·0022221 for base temperature of 60° F. Rise of temperature = 36° F.

2401 × [1 + (0·0022221 × 36)] = 2401 × 1·08 = 2593 ohms at 96° F.

Subtract original resistance . . .	2401
Resistance has risen	192 ohms.

Ex. (*d*). Matthiessen when experimenting found that a copper wire of 2,064 ohms at 0° C. had 2262 ohms at 24° C. What was the temperature coefficient of this sample?

Increase in temperature, 24° C.

$$R_t \div R_o = 1 + a$$

$$\frac{R_t}{R_0} = \frac{2262}{2064} = 1{\cdot}096 = 1 + a\,t, \text{ therefore subtract 1.}$$

$$\frac{1{\cdot}000}{0{\cdot}096} = a\,t, \text{ and } t = 24° \text{ C.}$$

∴ 0·096 ÷ 24 = 0·004, the temperature coefficient, at 0° C. of this sample.

Ex. (*e*). The resistance of some copper wire was measured at 5½° C. and found to be 96 ohms. It had a temperature of 30° C. when in use. Calculate its resistance to the nearest ohm.

The resistance R_0 at 0° C. must be found, i.e. $R_0 = R_t \div 1 + a\,t$, $= 96 \div [1 + (0{\cdot}004265 \times 5{\cdot}5)] = 96 \div 1{\cdot}02346 = 93{\cdot}8$ ohms at 0°C.

The resistance R_t will then be $93{\cdot}8 \times [1 + (0{\cdot}004265 \times 30)]$ $= 93{\cdot}8 \times 1{\cdot}128 = 106$ ohms at 30° C.

44. BALLAST RESISTANCES. Certain oxides of the rare metals have such a high resistance cold as to be practically insulators, but when heated they become relatively good conductors. Rods made of yttria and thoria, very similar materials to those used to impregnate gas mantles, were formerly employed as the light-giving agents in Nernst lamps, which were largely in use before the osmium, tantalum and tungsten lamps were invented. These rods were heated up either by a spirit flame or small electric radiator when they permitted the current to flow in the ordinary way. One could then "light" an electric lamp with a match! To prevent excess of current flowing through Nernst lamps they had a "ballast resistance" in series, consisting of a fine iron wire enclosed in a glass tube filled with hydrogen. This had a high positive temperature coefficient, while the Nernst rod had a large negative coefficient. The consequence was that the greater portion of any variation in voltage was taken up by the ballast resistance.

45. OHM'S LAW gives the connection between the e.m.f. in a circuit, the resistance of the circuit, and the current flowing round the circuit. It enables any one of these quantities to be found if the other two are known. (Fig. 33.)

It is equally true for a portion of a circuit, giving a similar relationship between the pressure across that portion, the resistance of that portion, and the current through it. (Fig. 34.)

Resistance is the quality or effect in a circuit, carrying a current, which obstructs or impedes the flow of the current, and which prevents a small e.m.f. producing a large current in the circuit.

Energy expended in passing a current through a conductor may appear in different forms. One is heating of the conductor. When the whole of the energy appears as heat, the resistance is the ratio of the p.d. across the conductor to the current through it.

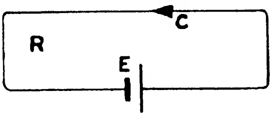


FIG. 33.

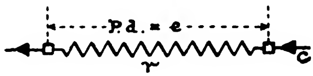


FIG. 34.

Any physical change may be considered as made up of a cause and an effect. When there is an opposition to a change of such a nature that it has some definite relationship to the proportion between cause and effect, such opposition may be termed a "resistance." In the electric circuit the cause is an electromotive force and the effect is the current, so that we can write,

$$\text{resistance of the circuit} = R = \frac{\text{cause}}{\text{effect}} = \frac{\text{e.m.f.}}{\text{current}} = \frac{E}{C}$$

If a steady current, c, flow through a conductor between whose ends a potential difference, e, is maintained and the conductor does not contain any e.m.f.'s, the ratio of e to c is defined as the resistance, r, of the conductor, or $r = \frac{e}{c}$. This equation does not represent any law but is the symbolical expression of the definition.

If the potential difference be changed to e_1 the current will alter to a new value, c_1 but there is no reason which could be stated beforehand why the ratio of e_1 to c_1 should remain unaltered, though this ratio would be the new resistance, r_1 of the conductor, or $r_1 = \frac{e_1}{c_1}$. There is no right to *assume* that $r_1 = r$. Consideration of other effects will show that they are seldom proportional to their causes, e.g. the speed of a train is not directly proportional to the h.p. of the locomotive, and the rate of flow of water in a pipe does not increase directly with the head. The law of variation, or absence of variation, with current can only be decided by experiment.

Ohm proved experimentally that the ratio of e.m.f. to current in an electric circuit, of perfect sameness as regards the material of the conductor, **corresponds to a real physical quantity**; that is, it has a definite value which is altered only when the nature or condition of the conductor is altered. Careful experiments have shown that provided the state of the conductor remains unaltered, the resistance as defined above is independent of the value of the current, i.e. it has the *same* value for all currents. Putting the law precisely, the ratio of potential difference between the ends of a homogeneous metallic conductor, not moving relatively to a magnetic field, to the current through it, is absolutely constant for a definite piece of metal at a constant temperature, and is called the resistance of that piece of metal. The value of r in the equation $r = \frac{e}{c}$ remains constant, no matter how e and c may be varied, provided the physical state of the conductor remains unaltered.

Resistance is regarded as a property of a conductor, for it depends on its material and dimensions, and only to a slight extent on its temperature.

Since the resistance of a circuit is defined as the ratio of the electromotive force in the circuit to the current through the circuit, the strength of the current in a circuit varies directly as the electromotive force, and inversely as the resistance of the circuit.

A conductor made up of different materials placed end to end may have e.m.f.'s produced by contact of the dissimilar materials. A circuit containing a secondary battery being charged has an opposing or back e.m.f. in it. A conductor moving in a magnetic field has an e.m.f. induced in it. In these cases the net or effective e.m.f. producing the current has to be taken, and this will be the difference,

$$\text{or, Resistance} = \frac{\text{Forward e.m.f.} - \text{Back e.m.f.'s}}{\text{Current}}$$

The terms *state* and *condition* used above refer in the first place to the temperature of the conductor. It has already been shown in dealing with temperature coefficient that a change of temperature generally produces a change of resistance. But the resistance is also influenced by other physical changes, such as a mechanical stress acting on the conductor. Tension, or compression, or torsion applied to a conductor usually alters the resistance. Again, the conductor must be continuous, in the sense that it must *not* consist of filings loosely packed in a glass tube, or a series of metal balls barely in contact with one another. A layer of dust on an insulator does not obey Ohm's law. Hence the use of the term *homogeneous* in the definition given.

Experiments show that a single cell will send a current through a very high resistance, say several hundred megohms. This could not have been foretold. If there be any potential difference in a closed circuit a current will flow. If the circuit be open, so that the resistance of the break be infinite, then there will be no current, however high that potential difference. But the break will be bridged by a spark, or the insulation between the open ends of the circuit will break down, if the pressure be raised sufficiently high.

The **proof** of the truth of Ohm's law is the agreement with expectations and calculations of the results of the millions of measurements of resistance which have been made. When assertions have been made questioning its truth, it has always been found that the experimenters have failed to observe the necessary precautions in making their tests.

It follows from Ohm's law that the current C through a circuit is directly proportional to the electromotive force E and inversely proportional to the resistance R. Also that the e.m.f. in a circuit is equal to the product of current and resistance, or,

$$R = \frac{E}{C}, \text{ and } C = \frac{E}{R}, \text{ and } E = C \times R.$$

In this simple form, however, the law is only strictly true for steady direct currents.

The law is applicable to any part as well as the whole of a circuit. Thus if we consider any portion of a circuit, Fig. 34, and know the resistance r, of that part, and the potential difference e, between its ends, the current flowing will be c, and

$$r = \frac{e}{c}, \text{ and } c = \frac{e}{r}, \text{ and } e = c \times r.$$

The truth of the following statements will be obvious—

(*a*) With a given pressure, if the resistance be doubled the current will be halved: if the resistance be halved the current will be doubled.

(*b*) If a circuit of low resistance be connected across terminals having a p.d. of a hundred or two volts, such as would exist between the two poles on a distribution board, the current would be very large. If the circuit consist of a few yards of not very thin copper wire, say, 0·1 ohm, such a current would be 1,000 to 2,000 amps., and the fuse in the circuit would melt immediately.

If, on the other hand, a high resistance be connected, such as a lamp intended to work at that p.d. and of, say, 1,000 ohms resistance, the current would be comparatively small, from 0·1 to 0·2 amp., or just enough to cause the lamp to light up.

(*c*) If the current is to be kept *constant*, and the resistance be increased, the pressure must be increased in the same proportion, and *vice versa.*

(*d*) With a given resistance, if the pressure be increased or lessened, the current will also be increased or lessened; in other words, the current will vary exactly as the pressure varies.

(*e*) Since volts ÷ amperes = ohms, and mhos are reciprocal to ohms, amperes ÷ volts = mhos, thus—

$$\text{as } R = \frac{E}{C} \text{ and } M = \frac{1}{R} \therefore M = \frac{C}{E}$$

where M stands for conductance in mhos.

Ex. (*a*). Three resistance of 1·09, 0·009 and 0·901 ohms are connected in series across a 50-volt circuit. Find the current through the circuit.

$$C = \frac{50 \text{ volts}}{1{\cdot}09 + 0{\cdot}009 + 0{\cdot}901} = \frac{50}{2} = 25 \text{ amps.}$$

Ex. (*b*), If a carbon lamp take 0·3 amp. at 200 volts, what would be the resistance of 500 such lamps in parallel when cold ?

$$\frac{200}{0{\cdot}3} = 666 \text{ ohms, each, hot} : \frac{666 \times 2}{500} = 2{\cdot}66 \text{ ohms, group, cold.}$$

Ex. (*c*). Three resistances are connected in parallel (Fig. 35), and in series with them is a battery having an e.m.f. of 6 volts and an internal resistance of 1 ohm. Find current in each resistance.

Resistance.	Conductance.		Current in each resistance.
2ω	0·5 mho		0·5 × 2·88 = 1·44 amp.
3ω	0·333 ,,		0·333 × 2·88 = 0·96 ,,
4ω	0·25 ,,		0·25 × 2·88 = 0·72 ,,
	1·083 ,,	= 0·923 ohm	
add *r*		= 1·000 ,,	
Resistance of circuit		= 1·923 ,,	
Total Current = 6/1·923 = 3·12 amps.			3·12 ,,
Current per mho = 3·12/1·083 = 2·88 amps.			

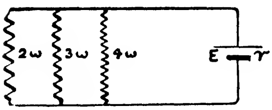


FIG. 35.

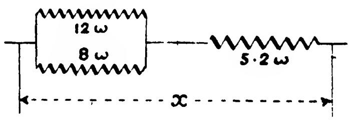


FIG. 36.

Ex. (*d*). Two resistances of 12 and 8 ohms are placed in parallel and in series with the combination is a resistance of 5·2 ohms. If a current of 4 amps. flows through the 12ω resistance, what is the p.d. between the extreme terminals ?

P.d. on R_1 = 4 × 12 = 48 volts with C = 4 amps.
C through R_2 = 48/8 = 6 ,,

Total Current = 10 ,,

P.d. on R_3 = 10 × 5·2 = 52 volts.

P.d. between extreme terminals = 100 ,,

46. BACK E.M.F. A counter e.m.f. or back e.m.f. is one which acts in *opposition* to the main e.m.f. or pressure in the circuit.

When a secondary battery is being charged, its own e.m.f. acts as a back e.m.f., for it is in opposition to that of the charging pressure. Thus a dynamo cannot charge a battery unless its e.m.f. be greater than that of the battery; and the e.m.f. or pressure available for sending current through the resistance of the circuit is that which is left when the battery e.m.f. is subtracted from the dynamo e.m.f.

When a direct-current motor is at work, it sets up a back e.m.f. which acts against the voltage impressed in the terminals of the motor, and therefore tends to reduce the current. Thus, supposing the resistance of the motor circuit were known, the current through the motor would be obtained by subtracting its back e.m.f., e, from the impressed voltage, V, and dividing the remainder by the total resistance R of the circuit, or—

$$C \text{ would equal } \frac{V-e}{R}$$

The back e.m.f. of a secondary battery or of a motor does not affect the application of Ohm's law to circuits containing them, except that they must be taken into account as just explained.

47. RESISTANCE may be either calculated or measured. Very often one method acts as a check upon the other. Comprehensively the methods may be classified as—

(*a*) Of the resistance of a wire or cable, when its length l, sectional area A, and the resistivity of its material ρ are known, then

$$R = \frac{l}{A}\rho \quad (\S 39).$$

(*b*) By Ohm's law, when the pressure and current, or other electrical quantities are known, then

$$R = E/C \quad (\S 45).$$

(*c*) Of the resistance of a circuit when the resistances of the various parts are known, or may themselves be easily calculated. (§32 and §38.)

Taking a and b together, we may write—

$\frac{E}{C} = \frac{l\rho}{A}$, so that if any four out of the five quantities are known, the fifth can be calculated.

Thus resistivity may be written—

$$\rho = \frac{E}{C} \times \frac{A}{l} \text{ or } \frac{E}{l} \Big/ \frac{C}{A}$$

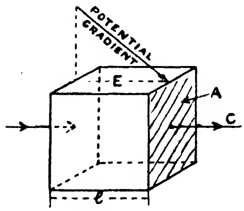


FIG. 37.

E is the p.d. across a length l, therefore $\frac{E}{l}$ is the p.d. between the ends of a piece of the material 1 in. long ; or, in words, it is the *volts per unit length.*

C is the total current through the material, therefore $\frac{C}{A}$ is the current flowing through an area of 1 sq. in.; or, in words, it is the *amperes per square inch.*

Resistivity and conductivity are reciprocal, so we may invert the symbols of one to get the other. Thus another way to define resistivity, in addition to saying that it is the resistance per inch cube, is

$$\text{Resistivity} = \frac{\text{Volts per unit length}}{\text{Amperes per unit area}} = \frac{E \times A}{L \times C}, \text{ and}$$

$$\text{Conductivity} = \frac{\text{Amperes per unit area}}{\text{Volts per unit length}} = \frac{L \times C}{E \times A}$$

Amperes per unit area is the *current density*, and volts per unit length is *potential gradient*, as may be understood by looking again at Fig. 37. This way of thinking of conductivity will be found of considerable assistance when it comes to studying the magnetic circuit.

48. ELECTRICAL POWER. When a current flows round a circuit electrical power is expended in, or absorbed by, the circuit.

It is necessary to take into account the pressure at which electricity is supplied, as well as the electricity itself Electricity costs nothing—it is everywhere, so to speak But electricity is not manifest, and therefore has no power to do work, until a difference of electrical pressure is set up. Electricity without pressure has no commercial value. The electricity supply authorities do not generate electricity, for that is impossible. What they really do, by means of dynamos or alternators, is to create and maintain a difference of electrical pressure.

As an analogy, take the case of the water company. They do not manufacture water, but they do create a difference of water level or water pressure; and it is this which causes water to flow through the network of pipes which distribute the supply. If we wish to run a water motor or turbine, a tank containing any number of gallons of water would in itself be of no use whatever if it were situated at a low level, say in the basement of the premises. We must not only have water, but "head" or pressure of water as well. Similarly with electricity.

If light or heat be given out from devices connected in a circuit, something must be absorbed. It is power that is absorbed in the circuit, particularly in those parts which have the greatest resistance, i.e. in which the light or heat is generated, and the power is due to a current being forced through the resistance of the circuit.

To send electricity through a given resistance at a given rate, a certain electrical pressure has to be applied. The higher the pressure the larger will the current be, and the greater will be the power expended. To send 1 amp. through 1 ohm requires 1 volt, but to send 1 amp. through 10 ohms requires 10 volts.

To send	through	requires	and power is	
1 amp.	7·46 ohms	7·46 volts	7·46 watts	
10 amps.	7·46 ,,	74·6 ,,	746·0 ,,	or 1 h.p.
100 ,,	7·46 ,,	746·0 ,,	74600·0 ,,	or 100 h.p.

The power is therefore not merely the current, nor the pressure, but the product of the two. If, in a direct current circuit, we multiply the e.m.f. by the current, the product will represent the total power expended in the circuit. Thus—

Power expended in whole circuit = e.m.f. × current.

Power expended in any part of the circuit = p.d. between the ends of that part × current through that part.

The latter statement follows from the fact that the e.m.f. is equal to the sum, or total, of all the p.d.'s in the circuit. In either a direct or alternating current—

Power expended in whole circuit = sum, or total, of power expended in each of the different parts of the circuit.

The power is exerted or expended; that is, dissipated in, or absorbed by, the materials comprising the conducting circuit and its environment. It is dissipated if converted into heat, which eventually is lost; and absorbed if reconverted into some other form, such as mechanical motion.

49. THE UNIT OF ELECTRICAL POWER is the *watt*, and is the power expended when a d.c. current of 1 amp. flows through a resistance, between the ends of which there

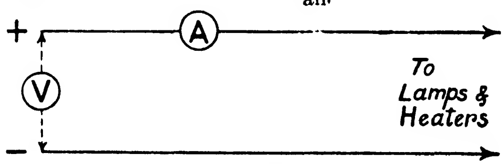


Fig. 38.

is a pressure of 1 volt. The symbol Pw is conveniently used to signify electrical power. Thus, (direct current)—

$$Pw, \text{ in watts} = \text{volts} \times \text{amps.} = E \times C,$$

and as, by Ohm's law, $E = C \times R$,

$$\text{also, } Pw = C \times R \times C = C^2R.$$

The multiples of the watt commonly used are—

the kilowatt = 1000 watts,

and the horse-power = 746 watts.

The power absorbed in a whole circuit containing, say, lamps and heaters, can be found if the pressure at the end of the circuit and the current flowing through it are known. One way of ascertaining these quantities is by means of a voltmeter, connected as at V, and an ammeter, connected as at A, in Fig. 38. For instance, if the voltmeter showed 110 volts and the ammeter 16 amps., the power in the circuit would be $110 \times 16 = 1760$ watts $= 1{\cdot}76$ kw.

The power absorbed in a portion of a circuit, say a heater *h*, could be calculated by ascertaining the p.d. at the terminals of *h*, by means of a voltmeter V in Fig. 39,

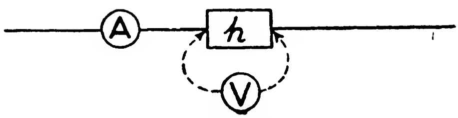


FIG. 39.

and the current by means of an ammeter A; and multiplying the two quantities together.

A given resistance R, when connected across E volts will pass a current C, and the power Pw absorbed will be $E \times C = C^2R$. If the pressure be doubled then the current will be doubled also, so that the power Pw_2 will be $2E \times 2C$ or $Pw_2 = 4\ (E \times C)$, or $4\ Pw_1$. That is to say, any electrical device, say a heater, coupled on a 200-volt circuit will take four times the power it would do if coupled to a 100-volt circuit. This also follows from the fact that if the current be doubled the value of the square will be four times the square of the original current.

The statement that $Pw = C^2R$ is only true, however, when the circuit has no back or *counter* e.m.f. in it.

In a circuit containing a motor or a secondary cell "on charge" there is a counter electromotive force which works against the circuit-pressure, and so makes the current less than it would otherwise be. Thus the power absorbed by a secondary battery being charged would not be given by the product C^2R, because the p.d. applied to the terminals of the battery would be partly used in opposing the counter e.m.f. of the battery, and partly in overcoming its resistance R. One portion of the p.d. would be equal to the counter e.m.f. of the battery, and the other portion to $C \times R$. Thus—

$$\text{Applied p.d.} = \text{counter e.m.f.} + (C \times R)$$

and $$Pw \text{ absorbed by battery} = \text{applied p.d.} \times C.$$

The product of $E \times C$ would give the power in such a circuit because the total pressure must be taken into consideration, as that which neutralizes the counter e.m.f. represents a factor of the power expended in the circuit. In short, whether a direct-current circuit contains a counter e.m.f. or not, its terminal pressure multiplied by the current will give the power therein. The formula C^2R, on the other hand, would *not* give the correct power in a circuit with a counter e.m.f., because it would not take account of that portion of the applied pressure which was neutralized by the counter e.m.f.

Ex. (*a*). A resistance of 25ω intended to absorb power on a 200-volt circuit is used on 100 volts and found ineffective. *State the probable reason.*

On 200 volts $C = 8$ amps. and $Pw = 8 \times 200 = 1600$ watts.
,, 100 ,, ,, $= 4$,, ,, $= 4 \times 100 = 400$,,

As the current and pressure are both halved, the power absorbed is only one quarter.

Ex. (*b*). Prove the law that the number of watts wasted in a resistance when the current is supplied at a constant voltage is inversely proportional to the resistance.

$$Pw = C \times E, \text{ and } C = E \times R$$

$$= \frac{E}{R} \times E, \text{ which is } \frac{E^2}{R}.$$ If E remains unaltered Pw is inversely proportional to R.

Ex. (*c*). A coil has 8ω resistance cold, but an hour after being connected across a 30-volt circuit it increases to 12 ohms. *Find power lost in each case.*

$$\text{Cold, } Pw. = \frac{30^2}{8} = \frac{900}{8} = 112{\cdot}5 \text{ watts}$$

$$\text{Hot, } Pw. = \frac{30^2}{12} = \frac{900}{12} = 75 \text{ watts.}$$

Ex. (*d*). What is the resistance in which 86,400 joules are wasted every ten minutes when 6 amps. passes through it ?

$$\frac{86{,}400}{600} \text{ (secs.)} = 144 \text{ joules per sec., or watts} : \frac{144}{6^2} = 4 \text{ ohms.}$$

Ex. (*e*). Two coils connected in parallel take a total current of 10 amps. at 230 volts. One coil absorbs 950 watts. What are the resistances ?

Current in both coils = 10 amps.
Current in first coil
= $Pw \div E$ = 950 ÷ 230 = 4·13 ,, and 230 ÷ 4·13 = 55·68 ohms.
leaving current in second coil = 5·87 ,, and 230 ÷ 5·87 = 39·19 ,,

These resistances in parallel have 23 ohms which allow 10 amps. to pass.

Ex. (*f*). How many 50-c.p. lamps, taking 1·2 watts per c.p. can be run off a dynamo giving 8 electric h.p. ?

Each lamp takes 50 × 1·2 = 60 watts, and 8 e.h.p. = 8 × 746 = 5968 watts.

5968 ÷ 60 = 99 to 100 lamps.

Ex. (*g*). Find the electric horse-power required to send 150 amps. through 9ω.

$$\text{e.h.p. required} = \frac{150^2 \times 9}{746} = \frac{202{,}500}{746} = 271 \text{ e.h.p.}$$

Ex. (*h*). Two resistances, *a* and *b*, respectively of 300ω and 200ω are connected in parallel with each other, and put in series with a third of 250ω What p.d. will be necessary in order that the circuit may consume 1500 watts ?

Joint conductance of *a* and *b* = 0·0033 + 0·005 = 0·0083 mho

∴ joint resistance = 120ω.

Then total resistance = 120 + 250 = 370ω.

Divide the watts by the resistance to obtain C^2.

Thus 1500 ÷ 370 = 4·054, and current = $\sqrt{4{\cdot}054}$ = 2·013 amps.

Pressure is 370ω × 2·013 amps. = 745 volts.

50. APPARENT POWER. Power expended in passing a current through a conductor may appear as a change in the neighbouring magnetic fields. When such a change takes place the result is the creation of a back or counter e.m.f. Then the statement made at the beginning of the last paragraph must be remembered.

The product of volts by amperes always gives the apparent power in *volt-amperes*. This is the same as the true power, in watts, in the case of incandescent lamps, whether on direct or alternating current, and in all other cases on direct current. It is also the same if, in an alternating current circuit, the current changes in direction simultaneously with the changes of direction of the pressure. Except in the case of lamps, this is not generally what happens in an alternating current (a.c.) circuit. Hence the product of a.c. volts by a.c. amperes does not usually give the true power in watts, but merely the *apparent power* in volt-amperes (v.-a.).

The ratio of true power to apparent power is called the *power factor*, and is expressed either as a percentage or as a decimal fraction.

True power in watts.	Apparent power in volt-amperes.	Power factor.
say 100	100	100% or unity
90	100	90% or 0·9
66	100	66% or 0·66

The meaning of this is explained fully when alternating currents are dealt with in Vol. II.* For the present it will be assumed, unless otherwise stated, that only direct currents are under discussion, or that, if alternating, the power factor is unity.

An analogy to the use of "power factor" is the case of a ship carrying freight. The earning capacity of the ship depends upon the size of its holds; that is, the cubic capacity available for stowing freight. The shipowner knows this perfectly well so he adopts alternative methods of charge. The ordinary way is to charge by weight, say 2s. 6d. per 100 lbs., which is equivalent to £2 16s. per ton, and would be commercial in the case of coal. Bulky and light articles would not be remunerative on this tariff, so if the shipowner is asked to carry these he charges, say, 1s. 3d. per cubic ft. This corresponds to 44·8 cubic ft. to the ton, for the total revenue to be the same, and as coal weighs 45 cubic ft. to the ton either scale of charge would bring in about the same money to the shipowner. In a similar way electricity supply authorities charge on alternative scales, so that their generating plant, which has a fixed volt-ampere capacity, may not be loaded up with a current at a low power factor without the purchaser having to pay.

* See also the *Power Factor Booklet* issued by the Electrical Apparatus Co., Ltd., for simple explanations of the meaning of this term.

A multiple of the volt-ampere, the kilo-volt-ampere (k.-v.-a.), is a unit often used in alternating current work, and is 1,000 volt-amperes. Thus the size or output of an alternator is spoken of as, say 3,000 k.-v.-a. (i.e. 3,000,000 volt-amperes).

51. ELECTRICAL ENERGY. Energy, or the capability of doing work, is measured by the amount of work done. The rate of doing work is the amount of work done per unit of time.

The rate of doing work, multiplied by the time in which the work is done, will give the total amount of work done. In other words, power × time during which it is exerted, will give the amount of work done.

Power, being the rate of doing work, is measured by the amount of work done in a given time ; and is got by dividing the work done by the time it takes to do it. Thus—

$$\text{Energy or work} = \text{power} \times \text{time} ;$$

$$\text{and power} = \frac{\text{work}}{\text{time}}$$

Work is done and energy expended when a force overcomes a resistance. When a current flows round a circuit, electrical work is done.

In the practical system of units, unit electrical work is done when a pressure of one volt sends a coulomb of electricity through a circuit.

The **joule** is the amount of work done by one watt in one second, or by one ampere flowing for one second under a pressure of one volt, or a volt-coulomb. The joule is defined as being equal to 10^7 units of work in the c.g.s. system, and is represented for practical use by the energy expended in one second by an ampere in an ohm.

If unit power, the watt, be expended for one second a joule of work, i.e. one watt-second, is done. The joule is thus sometimes called the watt-second, while the watt is sometimes defined as work done at the rate of 1 joule per sec.

$$\text{Thus joules} = \text{watts} \times \text{seconds}.$$
$$\text{But watts} = EC = C^2R$$
$$\therefore \quad \text{joules} = ECT = C^2RT = EQ$$

where T is the time in seconds. This gives us another definition of the unit of resistance: the ohm is such a resistance that one joule is expended in causing the transfer of one coulomb of electricity per second through the conductor.

Put into words the above equation means that the product of electrical quantity and electrical pressure gives electrical energy. As quantity = current × time, electrical energy on a direct current system, or on any system supplying lamps only, = pressure × current × time. If we multiply volts by amperes by seconds, we get watt-seconds or joules. But this unit is inconveniently small.

The **watt-hour** is a multiple of the joule, and is = watts × hours. As there are 60 × 60, or 3,600 seconds in an hour, it follows that a watt-hour = 3,600 watt-secs. or joules. This unit is still too small for commercial use, as it would lead to long rows of figures having to be set down.

The **Board of Trade Unit,** sometimes called the Kelvin, is defined to " mean the energy contained in a current of one thousand amperes flowing under an electromotive force of one volt during one hour " and therefore is equal to 1,000 watt-hours, or 1 *kilowatt-hour*. That is to say, if a consumer takes a constant number of watts, he will have received 1 Board of Trade unit when the number of watts, multiplied by the number of hours during which they have been taken, is equivalent to 1,000. Or when the number of amperes of unvarying current, multiplied by the pressure of supply, and by the hours during which such current has been passing, equals 1,000.

The power in watts, or the number of amperes flowing through any electrical installation, is not constant however;

for lights and motors are turned on and off at various times. It is therefore more correct to take into account the actual quantity of electricity that passes, and the actual pressure at which it is supplied ; thus—

1 Board of Trade unit = 1 kw.-hr. = 3,600,000 joules.

e.g. = 36,000 coulombs at 100 volts pressure

= 3,600,000 coulomb-volts.

A kilowatt taken constantly for 1 hr. = 1 kw.-hr., and

A horse-power taken constantly for 1 hr. = 1 h.p.-hr.

The connection between the units used to measure mechanical energy and the kilowatt-hour is—

$$\begin{aligned} \text{since } 746 \text{ watts} &= 1 \text{ h.p.,} \\ 746 \text{ watt-hrs.} &= 1 \text{ h.p.-hr.,} \\ \text{and } \quad 1 \text{ kw.-hr.} &= \frac{1000}{746} \text{ h.p.-hrs.} \\ \text{or } \quad 1 \text{ kw.-hr.} &= 1{\cdot}34 \text{ h.p.-hr.,} \\ \text{and } \quad 1 \text{ h.p.-hr.} &= 0{\cdot}746 \text{ kw.-hr.} \end{aligned}$$

Summarizing the foregoing—

Power is the *rate* at which work is done, or energy is consumed or developed in a circuit.

Work done or energy consumed or developed in a circuit depends upon the power exerted and the time during which it is exerted. A motor whose " load " does not vary, takes a certain amount of power to drive it, whether it runs for five minutes or five hours. But the amount of *work* done by this motor, or the amount of electrical *energy* consumed by it, will depend upon how long it runs.

If we multiply watts by seconds we get joules.

If we multiply watts by minutes we get watt-minutes.

If we multiply watts by hours we get watt-hours.

If we multiply kilowatts by hours we get Board of Trade " units."

Commercial unit of quantity of electricity—the ampere-hour, equal to 3,600 coulombs.

Commercial units of power—the watt, equal to 1 joule per second, and the kilowatt, equal to 1,000 watts.

Commercial units of energy—the watt-hour, equal to 3,600 joules, and the Board of Trade unit (or kilowatt-hour) equal to 1,000 watt-hours.

The student must not confuse the Board of Trade unit (B.o.T.U.) with the British Thermal Unit (B.Th.U.) which is explained later.

52. HEATING EFFECT OF THE CURRENT. Heat is a form of energy, and to develop heat some other kind of energy must be expended and work done. Heat developed in an electrical circuit denotes the expenditure of electrical energy, and its conversion into thermal energy. When a direct current flows round a metallic circuit, the whole of the work done by it goes to the development of heat. Heat generated means work done; consequently heat is a form of work, and may be measured in the same units as energy or work.

Whenever a current flows round a circuit heat is developed, and electrical energy dissipated. Circuits are consequently designed so that the conductors and wires shall "heat up" as little as possible. In such appliances as incandescent lamps and cookers, heat is wanted, and they are made to heat up as much, and lose as little heat, as possible.

53. JOULE'S LAW. The heat developed by a current in a conductor is proportional to the resistance of the conductor, the square of the current, and the time of its flow, or

$$\text{Heat (in joules)} = C^2RT = \text{amps}^2 \times \text{ohms} \times \text{seconds}.$$

When electrical energy is converted into thermal energy, the product of $E \times C \times T$ must be a measure of a definite amount of heat, if the whole of the energy so converted appears in this form.

With steady direct currents, as $R = \frac{E}{C}$, it would be equally correct to say: $H = C \times E \times T$. It is not written in this form generally, because with alternating currents the values of C which correspond with the values of E *at any instant* are not necessarily those which are indicated by instruments connected to the circuit. Hence, the statement $H = C^2 \times R \times T$ is always true, but $H = C \times E \times T$ is only correct under certain circumstances which do not always exist.

If an electric circuit contains no counter e.m.f.—that is to say, if there is no motor therein, no accumulators under charge, no electrolytic apparatus, or no inductive effects as with alternating currents—the *whole* of the electrical energy expended in the circuit will be converted into heat energy. Then H (in joules) $= C \times E \times T$.

If the current remains the same, the greater the resistance, the greater will be the heat developed; and the longer the current flows, the greater the heat developed. If the resistance remains the same, the heat in a certain time depends on the square of the current; that is to say, if the current be doubled, four times the amount of heat will be liberated, and so on. An electric kettle which boils a pint of water in 10 minutes on 200 volts would take 40 minutes on 100 volts, because the current would be halved when the pressure was halved, thus the power would be reduced to one quarter, and to get the same amount of energy into the kettle would require four times as long. It would take rather more, because heat would be lost to the air from the outside of the kettle for a longer period.

It is because electrical energy is the most convenient form, as well as one of the most easily controlled forms, of energy that it is so extensively employed for domestic heating, cooking and lighting, as well as in electric resistance and arc furnaces of widely differing sizes.

54. HEAT UNITS. Any unit of work is also a unit of heat, for heat is a form of work done. But heat is that form of work which is expended on any substance when its temperature is raised, therefore the units of heat and of work are closely allied.

The substance which is always obtainable in the same state, and which takes a lot of heat to raise it 1° C., is water. This 1° C., however, is of quite an arbitrary character, inasmuch as it is merely one-hundredth of the difference in temperature between freezing and boiling points. To raise 1 gramme of water 1° C. requires a definite amount of heat, but this has no simple relationship to the units of work, merely because of the haphazard choice of a scale of temperature. Further, the relation between a certain amount of work and a certain amount of heat must be the subject of experiment, one which is called the "determination of the mechanical equivalent of heat."

One *calorie* is the amount of heat required to raise one gramme of water (i.e. 1 c.c.) one degree centigrade in temperature, and is the metric thermal unit.

Joule's equivalent, represented by J, is the amount of energy equivalent to the heat unit selected, say, the calorie. Experiments prove that 1 calorie is approximately equivalent to 4·2 joules, which is therefore known as the mechanical equivalent of heat in metric measure. We have, therefore,

$$J\,H = CET, \text{ and } H \text{ (calories)} = CET/4{\cdot}2.$$

To express the same equivalent in calories per joule, the figure becomes 1/4·2 or 0·24. That is, 1 joule is equivalent to 0·24 calories, and

$$H \text{ (calories)} = 0{\cdot}24\,CET = 0{\cdot}24\,C^2\,RT.$$

The mechanical equivalent of heat could be found by passing a constant current of C amperes through a resistance R, between whose terminals the potential difference is E volts. The resistance strip might be of manganin 5 ft long and 0·25 in. wide and 0·03 in. thick exposing 60 sq. ins. heating surface to the water. It is immersed in, say, 2,000 grammes of water (i.e. 2,000 c.c.) in a glass vessel. The vessel and strip are equal to 47 grammes of water in their heat absorption, making a total of 2,047 grammes, M.

A current of 30 amps. C, at a p.d. of 8·634 volts E, is passed through R, for 180 seconds T. The temperature of the water is taken before turning the current on and again at the end of the test, and the result is a temperature rise of 5·45° *C*. Then

Electrical energy put in.	Heat energy got out.
$C \quad E \quad T$	$M \quad t°$
30 × 8·634 × 180	2,047 × 5·45
= 46,620 watt-secs. or joules.	= 11,156 calories.

and $J = 46{,}620 \div 11{,}156 = 4{\cdot}18$ joules per calorie,
or, the reciprocal of this = 0·239 calories per joule.

This test result has been carried out one decimal further than the figure given previously. Moreover, if the subject be investigated further, it will be found that there is a slight difference in the amount of heat a gramme of water requires to have imparted to it to raise it 1° C. in temperature, according to what the temperature is at which it starts. The figure 4·18 is known to be correct as an *average* for the whole range of temperatures when taken by 1° C. steps from 0° C. to 100° C. It is the *actual* figure for a rise of 1° C. from 16° C. to 17° C., as this happens to correspond with that average.

On the Continent large quantities of water are measured by the tonne, or metric ton, which is equal to 1 cubic metre of water and therefore weighs 1,000 kilogrammes. A multiple of the calorie, the large or kilogramme-calorie, is then used. This is the quantity of heat required to raise the temperature of 1 kilogramme of water 1° C. Thus 1 large calorie = 1,000 calories.

A metric ton of water would be raised 1° C. by 1,000 kilogramme-calories of heat.

Taking the metre as the unit of length and the kilogramme as the unit of weight, the unit of work or energy is the metre-kilogramme and—

1 metre-kilogramme = 100 × 1000 or 100,000 cm.-grms. = 100,000 × 981, or 98,100,000 dyne - cms. or ergs = 98,100,000 ÷ 10,000,000, or 9·81 joules = 9·81 × 0·238/1000, or 0·002335 kilogramme-calorie as the equivalent of 1 metre-kilogramme. The reciprocal of this gives the work equivalent of the kilogramme-calorie as 428·3 metre-kilogrammes.

The **British Thermal Unit** (abbreviated B.Th.U) is the amount of heat necessary to raise 1 lb., or 0·8 pint, of water 1° F. in temperature. The B.Th.U. = 778 ft.-lbs. A gallon of water weighs 10 lbs. and will therefore consume 10 B.Th.U.'s for every degree Fahrenheit its temperature is raised. A quart, being one fourth of a gallon, will consume 2·5 B.Th.U.'s per 1° F. rise. One B.Th.U. of heat energy = 1054 joules or 0·29 watt-hr. of electrical energy.

A **therm** is the multiple of the B.Th.U. used, for example, where coal-gas is sold by calorific value instead of by thousands of cubic feet, and is equal to 100,000 B.Th.U.'s.

The relationship between the B.Th.U. and the calorie is as follows—

As 1 lb. = 453·6 grammes, and 1° F. = $\frac{5}{9}$ths of 1° C.,

$\therefore$ 1 B.Th.U. = $\frac{5}{9} \times 453{\cdot}6$ = 252 calories.

While

As 1 gramme = 0·002205 lb. and 1° C. = 1·8 ° F.,

$\therefore$ 1 calorie = $1{\cdot}8 \times 0{\cdot}002205$ = 0·00397 B.Th.U.

The fact that water has not a fixed density has already been mentioned. Neither is its specific heat, nor the amount of heat required to raise unit mass by 1° C. exactly the same at different starting temperatures. Strictly, therefore, the temperature from which and to which the water is raised must be stated. Here again there is a discrepancy in the definitions often given of the two heat units—

the British = heat to raise 1 lb. of water from 60° to 61° F., and
the metric = ,, ,, 1 gramme ,, ,, 4° to 5° C.

As a matter of fact, there has been no consensus of opinion as to the temperature from which the rise of 1° should be taken.

The specific heat of water varies but little with variations of temperature up to boiling point, so we can afford to neglect the differences in commercial work. The variation is sufficient, however, to cause slight differences in the figures given in tables. For example, taking 4·2 joules as being exactly equal to 1 calorie, and 252 calories as equal to 1 B.Th.U., the equivalent of 1 B.Th.U. would be 4·2 × 252 = 1058·4 joules, whereas a figure approximating more closely to absolute accuracy is 1055 joules.

The best practice to-day is to deal with the **Mean Thermal Unit.** By this definition the B.Th.U. is one 180th part of the total quantity of heat required to raise 1 lb. of water from 32° F. to 212°. This is much the same as taking 68° F. to 69° F., since the heat required for this 1° F. rise is practically equal to the mean value between 0° F. and 212° F.

As the mechanical equivalent of heat is a figure arrived at by experiment, it has naturally varied from time to time as more accurate methods have become available. According to the best experimental evidence **1 B.Th.U. = 777·8 ft.-lbs.,*** thus, Joule's equivalent in English measure, or the amount of energy in foot-pounds equivalent to the B.Th.U. = 778 ft.-lbs., for practical purposes.

The following figures are those commonly used—

4·2 joules	= 1 calorie	0·24 calorie	= 1 joule.
252 calories	= 1 B.Th.U.	1·356 joules	= 1 ft.-lb.
3412 B.Th.U.	= 1 kw.-hr.	778 ft.-lbs.	= 1 B.Th.U.

The number of joules corresponding to a British Thermal Unit is found by going back to the erg. 1 ft.-lb. = 30·48 × 453·6 = 13,825 cm.-grms = 13,825 × 981, or 13,563,000 dyne-cms. or ergs = 13,563,000 ÷ 10,000,000 or 1·3563 joules = 1·3563 × 778, or 1055·18 joules as the equivalent to 1 B.Th.U.

Ex. (*a*). What *number of watt-hours* are necessary to boil a pint of water, from room temperature 15° C. to boiling point if all the heat be taken up by the water ?

A pint of water weighs a pound and a quarter, or 1·25 × 453·6 = 567 grammes.

$H = M \times t° = 567\ (100° - 15°) = 48{,}195$ calories.

4·2 joules = 1 calorie ∴ 48,195 × 4·2 = 203,219 joules or watt-seconds.

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* This portion of the subject is well worth a little more consideration and a full account will be found in *The Thermal Measurement of Energy*, by E. N. Griffiths (Cambridge University Press, 3s. 6d.).

3600 watt-secs. = 1 watt-hr. ∴ 203,219 ÷ 3600 = 56 watt-hrs. (This is a useful figure to memorize.)

Ex. (*b*). Find the *time* required to heat a quart of water from 62° F. to boiling without any loss and taking 400 watts.

Mass of water = 2 pints = 2·5 lbs. in weight.

Rise of temperature = 212° F. − 62° F. = 150° F.

B.Th.U. required = 2·5 × 150 = 375.

Foot-pounds required = 778 × 375 = 291,700.

746 watts = 1 h.p. or 746 watt-mins. = 33,000 ft.-lbs.

$$\therefore \frac{291{,}700}{33{,}000} \times 746 = 6595 \text{ watt-mins.}$$

$$\text{and } \frac{\text{watt-minutes}}{\text{watts}} = \text{minutes, i.e. } \frac{6595}{400} = 16{\cdot}49 \text{ (Time in minutes).}$$

Ex. (*c*). Find the *efficiency* of a 230-volt electric kettle, which raises 1,000 grammes of water from 16° C. to boiling point, with 3 amps. in 10·6 mins.

$$\text{Efficiency in \%} = \frac{\text{heat energy in water}}{\text{total heat energy supplied}} \times 100$$

Heat in water = Mass × temperature rise = 1000 × 84° C.
= 84,000 calories.

Heat supplied = $C \times E \times T$ = 3 × 230 × 10·6 × 60
= 438,800 joules.
= 438.800 × 0·24 = 105,000 calories

$$\text{and efficiency} = \frac{84{,}000 \times 100}{105{,}000} = 80\%$$

Ex. (*d*). How *many grammes* of water can be raised from 10° C. to boiling point in 20 mins. by 1·75 amps. at 200 volts with an efficiency of 81% ?

Energy put in = 1·75 × 200 × 20 × 60 = 420,000 joules
= 100,000 calories.

Efficiency 81%, leaves 81,000 calories in water.

Rise 90° C. therefore 81,000 ÷ 90 = 900 grammes.

Ex. (*e*). How *many degrees* F. will the temperature be raised if 19·54 units of electrical energy are expended in heating 600 lbs. of water in an electric urn, which loses 1 unit of heat for every 10 added to the water ?

746 watts = 550 ft.-lbs. per sec. ∴ 746/550 watts = 1 ft.-lb. per sec. or 746/550 watt-secs. or joules = 1 ft.-lb.

1 B.Th.U. = 778 ft.-lbs. ∴ 746 × 778/550 (joules) = 1 B.Th.U. or 746 × 778/550 × 60 × 60 = 0·29313 watt-hrs. = 1 B.Th.U.

19·54 units (gross) = 19·54 × 1000 = 19,540 watt-hrs., and 19540/0·29313 = 66,660 B.Th.U. (gross).

With loss of 1 in 10 then 66,660 × 0·9 = 60,000 B.Th.U. (net), and B.Th.U./lbs. = 60,000/600 = 100° F. rise in temperature.

If the material heated be something else than water, its specific heat will be different from unity. Then the energy, in calories, required will be = mass in grms. × specific heat × required temperature rise in C°.

55. EFFICIENCY is the term employed to express how near to perfection is a process or means for the conversion of one form of energy to another. Perfection means that the conversion is complete and that no loss takes place in the process. If the conversion be from electrical energy to heat then the whole of the energy is converted into heat and there is no loss, although some of the heat may not be available exactly where wanted. The efficiency of an electric radiator is always 100 per cent inasmuch as all the electrical energy put into it is converted into heat. The *effectiveness*, however, may be quite different from the efficiency, as the satisfaction given to a user of an electric radiator depends upon how near it approaches to the thing the user commonly employs with a similar object, namely a coal fire. A coal fire gives out radiant energy at a red heat, and a radiator to be really effective must do the same.

The **conversion of energy** from one form to another is usually accompanied by heating of the means employed in making the conversion, although such heating is quite undesired and would be avoided were it possible. The conversion of mechanical power into electrical power by a dynamo, or of electrical power into mechanical power by a motor, cannot be performed without some loss of power in the dynamo or motor.

The efficiency of a dynamo or motor is the ratio of the power given out to the power absorbed, and is generally expressed as a percentage, although it might equally well be expressed as a fraction. The mechanical power required to drive a dynamo is termed the input. The electrical power given out by a dynamo is termed the output. The input to a motor is the electrical power necessary to drive it, and the output is the mechanical power developed by it. The input to an electrical transmission system is the electrical power measured at the end nearest the generator ;

and the output, the electrical power delivered to the other end.

$$\text{Efficiency in } \% = \frac{\text{output}}{\text{input}} \times 100$$

An electric kettle is employed to boil water, and its efficiency as a means of doing so is heat imparted to the water ÷ total heat supplied to the kettle and the water. An electric lamp is intended to give light, and its efficiency as an illuminating agent is light given out ÷ electric power absorbed by the lamp.

The theoretical number of heat units necessary to heat any given quantity of water depends on the number of degrees through which its temperature is to be raised. But the actual number necessary for the work will also depend upon the efficiency of the electrical heating apparatus, and upon the temperature and stillness of the surrounding air. If it takes a certain number of watt-hours to heat a certain quantity of water to boiling point in five minutes, it will take a greater quantity if fifteen minutes are allotted to the operation, for the water will have so much more time in which to lose heat.

The electrical energy expended in or absorbed by an electrical circuit must reappear as some other form of energy. In charging a secondary-battery, the greater portion of the electrical energy is converted into chemical energy, an electro-chemical action taking place. A secondary cell absorbs electrical energy when it is being charged and gives about three-quarters of this energy out again when it is discharged. The remaining 25 per cent is represented by the heating of the liquid, plates and connections. When a magnet does work in attracting its armature, there is an absorption of energy which is stored up in the magnetic flux.

As energy, which does not appear in the form sought for in a process of conversion, is lost when converted into heat, a common expression is to say that the lost or inconvertible energy is degraded into or dissipated as heat.

56. RATE OF HEATING. A practical application of heating is the provision of hot water for domestic purposes.

The greatest drain on a hot-water supply occurs when one wants a bath. An ordinary domestic bath takes about 30 gallons of water, that is 300 lbs. The average bath temperature is 110° F. or say a rise of 50° F. above cold tap temperature of 60° F. This means that the bath water contains 300 × 50, or 15,000 B.Th.U.

Assuming the time of filling the bath was 7 mins., then the *power required* would be 50 h.p.! This follows, since 50 × 746 × 7 gives 261,000 watt-minutes; and the water contains 15,000 B.Th.U. ÷ 3,412, or 4·396 kw.-hrs., or 4,396 × 60 = 263,760 watt-mins., which is approximately the same.

If the bath had to be filled in 3½ mins. it would require 100 h.p., but if about a quarter of an hour could be given then 25 h.p. would suffice. It is not surprising that the public find electric supply authorities rather disinclined to provide the power for hot water heated on the spot at the time it is required. The alternative is to conserve or *store-up heat* in the same way as is done by the kitchen boiler. If we allow the difference between 4,396 and 4,800 watt-hours for the loss in heat from the storage vessel, then only 200 watts continuously throughout the 24 hrs. will give us the 4,800 watt-hours required. This is the principle upon which "all-electric houses" are supplied with hot water. Owing to the high load-factor, or continuous user of power, the price per unit is a low one, often ½d., and an ordinary flat in London can be supplied in this way with energy to heat all the water required for a round figure of £5 yearly.

57. ENERGY AND HEAT EQUIVALENTS.

	Joules.	Foot-pounds.	Calories.	B.Th.U.
1 joule =	1·000	·738	·238	·000
1 ft.-lb. =	1·356	1·000	·324	·001
1 calorie =	4·18	3·081	1·000	·004
1 B.Th.U. =	1055·	778·	252·	1·000
1 watt-hr. =	3600·	2654·	864·	3·412
1 h.p.-hr. =	2680000·	1980000·	641000·	2545·
1 B.o.T.U. =	3600000·	2654155·	864000·	3412·

QUESTIONS—CHAPTER II

1. Explain the difference between a charge and a current of electricity, and give the units in which each is measured.

2. Show clearly by explanation, and sketches, what is meant by "fall of potential" round a circuit. Under what conditions is the fall of potential round a circuit uniform ?

3. Arrange the following in their order of conductance : platinum, platinoid, copper, bismuth, German silver; and the following in their order of resistance : silver, ebonite, aluminium, iron, wood and manganin.

4. Explain fully the difference between conductance and conductivity, and between resistance and resistivity.

5. Three wires have resistances of 1, 2 and 3 ohms respectively. What will be their joint resistance when they are coupled together first in series and then in parallel ? *Ans.* 6ω : $6/11\omega$.

6. Calculate the joint resistance of 2 ohms in parallel with 5 ohms and these joined in series with 12 ohms. *Ans.* $13\frac{3}{7}$ ohms.

7. State the laws of current distribution in divided circuits. Twelve wires, each of 1 ohm resistance, are joined up to form a skeleton cube. Show that the resistance between diagonally situated corners is five-sixths of an ohm.

8. Twelve wires, each having 1 ohm resistance, are joined up to form the edges of a cube. The joints are electrically perfect. Show that the total resistance of this system taken between two corners of the cube on the same edge is 7/12 of an ohm.

9. How is the resistance of a conductor affected by the lengths and by the cross section of the conductor ?

10. A certain length of copper wire has a cross-section of ·003 sq. cm., and a resistance of $72\,\omega$. What will be the resistance of a wire ·018 sq. cm. cross-section, and of equal length ? *Ans.* $20\,\omega$.

11. The resistance of the ohm is approximately that of a column of mercury 106 cms. long and 1 sq. mm. in section at 0° C. What would be the resistance of a column of mercury 1 metre long and 0·5 of a sq. mm. cross-section ? *Ans.* $1{\cdot}887\,\omega$.

12. If two carbon rods are taken, one a metre long and a centimetre in diameter, and the other an inch long and a hundredth of an inch in diameter, what will be the relative resistances ? *Ans.* 1 and 39·37.

13. The resistance of a copper wire ·134 in. in diameter and 1,760 yds. long is 3·128 ohms. Calculate the resistance of 440 yds. of a wire of the same metal ·065 in. in diameter. *Ans.* 3·323 ohms.

14. A piece of wire, 20 ft. long and ten thousandths of an inch diameter, is found to have double the resistance of another wire of the same metal 15 ft. long and of unknown diameter. What is the diameter of the second wire ? *Ans.* 0·01225 in.

15. The resistance of a bar of iron 1 yd. long, weighing 1 lb. is 0·00174 ohm. Calculate the resistance per mile of a wire having the weight of 400 lbs. per mile. *Ans.* 13·47 ohms.

16. A wire made of a certain alloy, of diameter 0·09 in., has a resistance of 0·047 ohm per yd. Find the specific resistance of that alloy. How many yards of the same material, if drawn to a

diameter of 0·018 in., would have a resistance of 100 ohms ? *Ans.* ρ = 8·3 microhms per inch cube, 85·11 yds.

17. Calculate the resistance of 1 mile of copper conductor having a cross-sectional area of 0·137 sq.in. *Ans.* 0·3052 ohm.

18. A certain length and gauge of platinoid wire has a resistance of 30 ω. How much longer must an annealed copper wire (of the same gauge) be to give the same resistance ? *Ans.* 20·73 times.

19. A certain hard drawn copper wire has a resistance of 2·3 ω. What will be the resistance of a manganin wire of similar length and gauge ? *Ans.* 68·12 ω.

20. Calculate the resistance of 1,000 yds. of copper wire a tenth of an inch in diameter. *Ans.* 3·025 ohms.

21. Platinum has six times the specific resistance of copper ; what would be the relative diameters of two wires of these metals of equal lengths and equal resistances. *Ans.* 1 and 2·45.

22. The resistance of 1 mile of copper wire is 3·128 ohms, and the diameter is 0·134 in. Calculate the resistance of ½-mile of German silver wire 0·065 in. diameter, having given that the specific resistance of German silver is 13 times that of copper. *Ans.* 43·2 ohms.

23. If 75 yds. of 7/16 cable are in parallel with 50 yds. of 19/20 what is the joint resistance ? A single No. 16 wire has a resistance of 0·8 ohm per 100 yds. ; a single No. 20 a resistance of 2·75 ohms per 100 yds. ; and a stranded conductor has 3 per cent more resistance than a solid conductor of the same cross-section. *Ans.* 0·04041 ohm.

24. What effect has variation of temperature upon the resistance of copper ? What is meant by temperature coefficient ? Give some indication of the relative temperature coefficients of copper, platinoid and manganin, and explain how this bears upon the selection of a material for the wire of testing coils.

25. Draw up a table of the different classes of liquids classified according to their power of conducting currents, giving examples of each class. How does a rise of temperature affect the conductivity of the different classes ?

26. State the effect produced by heat, causing a change of temperature, on the insulation resistance of the following materials : a glass insulator, a piece of rubber, mica, marble, paper as used for the insulation of cables, and the field magnet coil of a dynamo.

27. How does the resistance of the following vary with temperature : an iron wire, a German silver resistance, the internal resistance of a secondary battery ?

28. How does increase of temperature affect the resistance of carbon ? Is it similar or different to metals in this respect ?

29. A metal lamp takes a current of 0·3 amp. when working at 200 volts ; calculate the hot resistance of 100 such lamps working in parallel, and state what would probably be the resistance of each lamp when cold. *Ans.* 6·66 ω : 100 ω.

30. The current through a carbon filament lamp is 0·65 amp. and the p.d. across it is 130 volts. What is the resistance of the lamp when working and what would probably be the resistance cold ? *Ans.* 200 ω : 400 ω.

31. A coil of copper wire has a resistance of 50 ohms when its temperature is 60° F. After a current has been passing through it for some time it is found that its resistance has increased to 55 ohms. Calculate the temperature of the coil. *Ans.* 105° F.

32. Find the specific resistance of a material if a length of 1,000 metres of a cross-section of 1 sq. mm. has a resistance of 29 ohms at 15° C. If the same length has a resistance of 32·5 ohms at 45° C., find its temperature coefficient of resistance. *Ans.* 2·9 microhms per cm. cube : $a = 0{\cdot}00402$ per ° C.

33. A wire changes its resistance from r ohms to R ohms by an increase of temperature of n degrees ; construct a formula which will enable the change of resistance for any other change of temperature to be determined.

34. What is Ohm's law, and say whether it applies accurately to varying or alternating currents as well as to steady currents ? If not, why not ?

35. Define shortly electromotive force, resistance and current, and explain exactly what is meant by saying that the electrical resistance of a given wire is constant for the same temperature and independent of the current passing through the wire.

36. Explain what you understand by the terms "resistance" and "conductance" as applied to electric circuits. Why is it that even if the resistance of a circuit is as great as ten thousand ohms it cannot altogether stop the current from a single cell ?

37. What is the approximate resistance of one mile of No. 16 S.W.G. (0·064 in. diameter) high conductivity copper wire, and what current will flow if its ends are connected with a pair of terminals having a p.d. of 50 volts ? *Ans.* 13 ohms : 3·846 amps.

38. Two resistances of 5 and 8 ohms respectively are placed in parallel and in series with this combination is a resistance of 4 ohms. If the p.d. between the extreme terminals is 100 volts, what will be the p.d. between the terminals of each resistance ? *Ans.* 43·48 : 43·48 : 56·52 volts.

39. Three lengths of cable of which the resistances are respectively 0·035, 0·025, and 0·013 ohm are connected in parallel, and used to carry a current of 80 amps. How much of this current flows through each of the three cables ? *Ans.* 15·7 : 22 : 42·3 amps.

40. A lamp circuit is supplied at a pressure of 100 volts. There are 42 lamps in parallel and the resistance of each lamp is 150 ohms. How much current will the circuit take when all the lamps are on ? *Ans.* 28 amps.

41. How many horse-power are required to drive a current of 100 amps. through a resistance of 7½ ohms ? *Ans.* 100·5.

42. If three conductors having resistances of 1·5, 2, and 2·5 ohms respectively are connected in series across a 150-volt circuit, what would be the voltage drop across each, and the total power absorbed ? *Ans.* 37·5 : 50 : 62·5 volts : 3·75 kws.

43. If the three conductors in question 42 were connected in parallel across the same circuit, what would be the current in each, and the total power absorbed ? *Ans.* 100 : 75 : 60 amps. : 35·25 kws.

44. Prove that resistance = Pressure²/power. How many foot-pounds of work are done when a current of 5 amps. flows for one

minute in a circuit across the terminals of which a potential difference of 20 volts exists ? *Ans.* 4423·8.

45. A current of 10 amps. flows through a wire of 100 ohms resistance. State at what rate energy is being expended in this wire in foot-pounds per second. *Ans.* 7373.

46. Two lamps of 100 and 150 ohms each, when running, are put in parallel with each other, and the pair is put in series with a lamp of 100 ohms. What e.m.f. will be needed on the system in order that it may consume 250 watts ? *Ans.* 200 volts.

47. The current taken by two resistances in parallel with an applied p.d. of 50 volts is 15 amps. One of the resistances takes 450 watts. What are the values of the resistances ? *Ans.* $5\frac{5}{9}$ and $8\frac{1}{3}$ ohms.

48. Three resistance coils in parallel consume 500 watts when a p.d. of 50 volts is applied to them. The resistances of two of the coils are 15 and 25 ohms respectively; find the resistance of the third coil. *Ans.* 10·71 ohms.

49. How many horse-power are required to drive a dynamo lighting 1,230 lamps, each taking 0·3 amp. at 200 volts, with a combined efficiency of dynamo and circuit of 90 per cent ? *Ans.* 110 h.p.

50. What do you understand by terms " energy " and " power " ? State the units in which these quantities are measured, both mechanically and electrically, and the relation between them.

51. What is the resistance of an electric heater which takes 10 amps. on a 230 volt circuit, and what will be the consumption of electrical energy per hour ? *Ans.* 23 ohms : 2·3 units.

52. Define the c.g.s. units of current, potential difference, resistance, power and energy, and state their relations to the ampere, the volt, the ohm, the horse-power and the Board of Trade Unit respectively.

53. The price of electrical energy in a certain town is 4d. per B.o.T.U., and the supply pressure is 200 volts. An electrical energy meter on this circuit has a resistance of 10,000 ohms in its pressure coil ; calculate the cost of the energy wasted in this coil in a quarter of a year. *Ans.* 2s. 11d.

54. A motor, taking 100 amps. from a 220-volt supply, is running 8 hrs. a day and 6 days per week. What is the annual cost of running when the cost of electrical energy is 2d. per unit ? *Ans.* £457 12s.

55. If a motor of 10 h.p. has an efficiency of 85 per cent and runs at full load for 12 hours continuously, how many B.o.T.Units will it use ? *Ans.* 105·3.

56. If a motor takes 185 amps. at 460 volts and gives 80 h.p. what is its efficiency, and how many B.o.T.Units will it use per hour ? *Ans.* 70·13 per cent : 85·1.

57. What is the law according to which the amount of heat generated by a current varies with the current and the resistance of the conductor ? If a wire has a resistance of an ohm and is traversed by a current of 10 amps., what is the energy per minute wasted in it expressed in calories ? *Ans.* 1,428.

58. A current of 100 amps. passes through a conductor whose

resistance is 10 ohms. How many British Thermal Units of heat does it develop in a minute ? *Ans.* 5,687.

59. A current of 10 amps. flows through a resistance of 5 ohms for 6 seconds, and another current of 6 amps. flows through a resistance of 7 ohms; during what time must the latter current flow in order that the amount of heat generated in the two cases may be the same ? *Ans.* 11·9 secs.

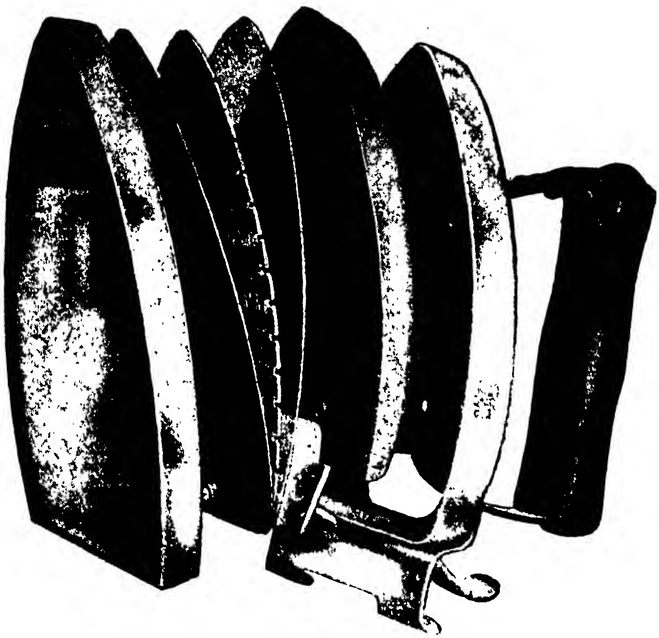


FIG. 39A.—EXAMPLE OF ELECTRIC HEATING.
DOMESTIC IRON, OPENED OUT. (COSMOS TYPE.)
(*Metropolitan-Vickers Supplies Ltd.*)

60. A heater has three similar resistance elements arranged for high, medium and low heating. Show how the three elements might be arranged to give a uniform variation in the three stages, stating the relative values of heating thus obtained. Temperature coefficient negligible. *Ans.* Either (*a*) all in series 0·33 ; one resistance, 1 ; all in parallel 3, or (*b*) one resistance, 1 ; two in parallel, 2 ; three in parallel, 3. (See note on page 94.)

61. What current will a 220-volt electric kettle take to heat a

quart of water, whose temperature is 15° C., to the boiling point in 10 mins. ? *Ans.* 3·05 amps.

62. Find the power required to boil a quart of water in five minutes, if the initial water temperature be 12° C., and the kettle used has 90 per cent efficiency. *Ans.* 1,545 watts.

63. 1,281 grammes of water have to be heated from 10° C. to 90° C. in an electric kettle, allowing a heat loss of 15 per cent. If the kettle has a resistance of $66\frac{2}{3}$ ohms, what must be the voltage of the circuit to supply the energy required in 14 minutes ? Power required = 600 watts, ∴ E = 200 volts.

64. Find how long it will require to raise a quart of water from 56° F. to 200° F. in an electric kettle having 95 per cent efficiency and taking 2 amps. at 200 volts. *Ans.* 998 secs. = 16·6 m.

65. An electric kettle, having an efficiency of 85 per cent, is required to raise the temperature of one pint of water from 15° to 90° C. in 5 mins. If the supply is at 250 volts, calculate what resistance the heating element must have. *Ans.* 89·66 ohms.

66. How many litres of water can be heated from 20° C. to 92° C. for one penny when electrical energy costs $1\frac{1}{4}$d. per Board of Trade Unit, ignoring heat losses from boiler ? *Ans.* 9·57 litres.

67. What will it cost, at $1\frac{1}{2}$d. per unit, to heat up a gallon of water from 10° C. to 90° C. in an electric urn, assuming that one-tenth of the energy supplied is lost by radiation. *Ans.* 0·703d.

68. A water-heater takes 500 watts and contains 1 litre of water at 5° C. If the efficiency = 80 per cent, what will be the temperature of the water after a quarter of an hour ? *Ans.* 91·12° C.

69. A cylinder containing 1,000 grammes of oil, having a specific heat of 0·9, contains a resistance coil of 8 ohms. The terminals of the resistance are connected to a 100-volt supply. How long will it take for the oil to rise 50° C. in temperature, assuming that the loss of heat is 10 per cent of the whole heat produced and that the heat capacity of the containing vessel is equivalent to 200 grms. of water ? *Ans.* 3 mins. 24·3 secs.

70. A resistance of 30 ohms is immersed in a vessel of oil and connected to 120-volt mains. Find to what steady temperature the vessel will rise, if when the resistance is not in circuit the vessel falls in temperature at the rate of 0·0014 $t°$ per sec., where $t°$ is the ° C. above the surrounding air. The heat capacity of the vessel and contents is 1,000 calories for 1° C. *Ans.* Calories per second gained = 114·8, and calories per second lost = 0·0014 × $t°$ × 1000, ∴ $t°$ = 114·8/1·4 = 82° C.

Note.—In questions 61 to 70 take one gallon = 10 lbs. ; 1 pint = 567 grammes ; 1 quart = 1134 grammes ; 1 litre = 1000 grammes ; and 1 calorie = 4·18 joules.

CHAPTER III

CONDENSERS AND ELECTRO-MAGNETS

58. CAPACITY. When electricity is at rest on a body it is spoken of as a *charge.* Every conductor is said to have a certain *capacity* for electricity, though not in quite the same sense as a jug has a certain capacity for water, as the capacity of a conductor depends upon its position and surroundings.

Static charges of electricity reside only on the surface of bodies, as is proved by the fact that the thickness of the conductor has no effect on the charge, other things being equal. Each part of a charge repels each other part, hence these respective parts are repelled as far as possible, that is, to the surface of the body to which they have been imparted. Charges may be positive or negative. Equal charges of unlike character annul one another. Equal charges of the same sign give a charge double that of either.

The capacity of a conductor is measured by the number of coulombs of electricity it will hold when its potential or pressure is raised by a given amount. Thus, if one conductor requires three coulombs of electricity to raise its potential to one volt, while another requires only one coulomb to raise its potential to the same degree, the capacity of the former conductor is three times that of the latter.

59. THE CONDENSER. When two conducting plates are placed opposite each other, with a sheet of insulating material between them, the arrangement is termed a *static condenser.* A condenser may be defined as an apparatus for "condensing" or "accumulating" a charge of electricity. This is effected by increasing the capacity of a conductor by bringing it near another conductor. The action of a condenser depends upon *electrostatic induction,* and the attraction of unlike charges. If an insulated conductor be far removed from other conductors—hung up in the middle of an empty room, for instance—a certain amount of electricity may be put into it, or abstracted from it, before its potential is raised or lowered to a given degree. But if that conductor be near to (but not touching) another conductor, especially if the latter be earth-connected, the capacity of the first conductor is increased. In other words, it will be possible to impart more electricity

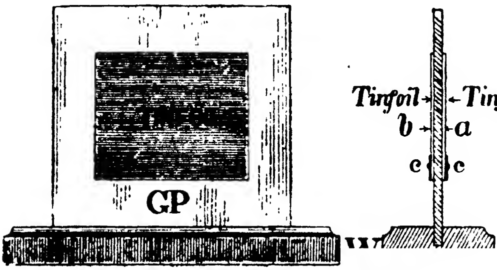


Fig. 40.—Simple Condenser.

to it, or take more away from it, before its potential is raised or lowered to the same degree as before.

Fig. 40 represents the simplest form of condenser. GP is a glass plate, say one foot square, with a sheet of tinfoil about 8 ins. square gummed on each side. The glass plate fits upright in a slot cut in a block of wood W. The tinfoil sheets are placed in the middle of each side of the glass plate so that there is a strip of glass 2 ins. wide all round. The glass, where not covered by tinfoil, should be varnished. The tinfoil sheets, marked *a* and *b* in the drawing, are called the *coatings* of the condenser. They should each have a little strip of tinfoil *cc*, soldered or fixed on, so as to form a kind of catch for the end of a wire, when it is desired to connect the condenser with anything.

The *Leyden jar* is a simple condenser in the form of a deep glass jar, the inside and outside of which are coated a part of the way up with tinfoil.

The insulating material which separates the coatings of a condenser, and which may be glass, mica, paraffined paper, air, or other good insulator, is called the *dielectric*; and the power of any insulating material to convey through itself the influence due to an electrified body, is termed its *specific inductive capacity* or *dielectric constant.* This property of an insulator is quite distinct from its resistivity value.

Fig. 41 represents diagrammatically the construction of a condenser for practical work, made by interleaving sheets of tinfoil with good-quality paper which has been previously dipped in melted paraffin wax. This not only prevents the paper from getting damp, but fills up its pores and renders it altogether a better insulator. The thick lines P represent the paraffined paper or other suitable dielectric—mica, for instance—and the thin lines T the tinfoil sheets. A great number of sheets are used, and alternate ones are connected together to form the two *coatings*, or *poles* of the condenser; the whole being compressed tightly together.

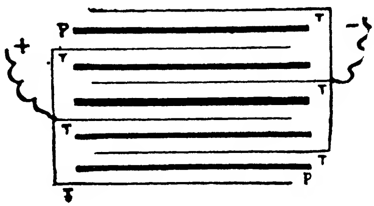


FIG. 41.—DIAGRAM OF CONDENSER.

60. ACTION OF A CONDENSER. The action of a condenser may be explained by saying that it accumulates electrical energy when one coating or set of plates is connected with one terminal of a source of electromotive force, and the other coating is connected with earth, or with the other terminal of the source.

The following experiments with an influence machine will give an idea of the action of a condenser; but, with such high-pressure electricity, it is necessary to use one with a stout, thick dielectric, such as a simple condenser (Fig. 40), or a Leyden jar.

Ex. (*a*). Disconnect the Leyden jars from the influence machine. On working the latter, a continuous stream of thin sparks will pass between the terminals.

Ex. (*b*). Connect either of the coatings of a simple condenser to one of the terminals, the other coating being insulated. No appreciable difference will be noticed in the action of the machine.

Ex. (*c*). Connect one of the coatings to one terminal *T* of the machine, and the other coating to the other terminal T^1

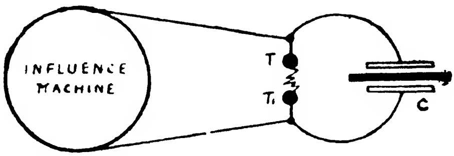


FIG. 42.—ACTION OF CONDENSER.

(Fig. 42). The machine when worked, instead of giving a continuous stream of sparks, will give sparks at intervals only, but they will be much thicker than before.

This result may be explained by assuming that electricity streams into the condenser *c* until it is fully charged, and that the condenser then "overflows," so to speak,

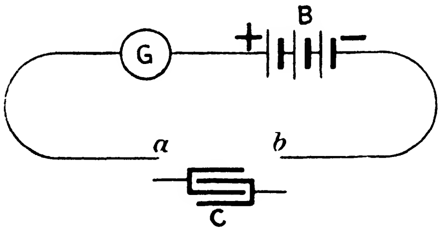


FIG. 43.—ACTION OF CONDENSER.

and gives a very bright thick spark, which discharges the condenser. This action is repeated at intervals, so long as the influence machine is worked.

A kindred series of experiments may be performed with apparatus arranged as shown in Fig. 43. Here **C** is a large-capacity condenser on the principle illustrated in Fig.

41, **B** a battery of a few cells, and **G** a sensitive galvanometer. The battery and galvanometer are connected in series, and wires *a b* attached to the free ends of each.

Ex. (*d*). Connect *a* to one of the poles of the condenser, and leave *b* unconnected. There will be no movement of the galvanometer needle, this indicating that practically no transference of electricity has taken place.

Ex. (*e*). Leaving *a* connected with one pole of the condenser, hold *b* in contact with the other pole. There will be a momentary deflection of the galvanometer needle, indicating a flow of electricity from the + pole of **B** through **G** to the pole of the condenser connected with *a*; and we may assume that an exactly equal amount flows out from the condenser through *b*. The potential of the pole of the condenser connected to *a* is then the same as the + pole of **B**, and that of the other pole is the same as the - of **B**. After the momentary deflection the galvanometer needle will return to zero, showing that no current is then passing.

Ex. (*f*). Disconnect *a* and *b* from **C**, take **B** out of circuit, and connect *b* straight up to **G**. Then hold *a* and *b* to the poles of **C**. A momentary discharge current will thereupon flow through **G** in the *reverse* direction to the first current.

An insulated wire or cable consists of a conductor surrounded by a dielectric and therefore behaves like the condenser **C**.

61. UNIT OF CAPACITY. The unit of capacity is called the *farad*. A condenser has a capacity of one farad when it requires a charge of one coulomb to raise the p.d. at its terminals to 1 volt. A condenser of such a capacity, however, would be much too large for practical work; in fact, an average size of condenser used in testing is one having a capacity of 1 microfarad, i.e. one-millionth part of a farad, written 1 mfd.

62. THE CAPACITY OF A CONDENSER depends upon three things—

(*a*) The superficial area of the two plates (or whatever is equivalent to them).

(*b*) The distance these plates are apart or separated.

(*c*) The specific inductive capacity of the insulating material or substance which is in the space between them.

The larger the area of the plates, or electrodes, and the smaller the distance between them (i.e. the closer they are together) the greater the capacity of the condenser.

The specific inductive capacity of air is taken as the base or unity and other substances are compared with air. Paraffin wax is about twice as good as air, ebonite about three times, mica about six, and glass about seven times. Thus, a condenser formed of two brass plates, separated by air, would have some seven times its original capacity if the space between them were filled with glass instead of air. A condenser made with mica as dielectric is smaller and more compact for a given capacity than one of the cheaper type, with paraffined paper.

63. ENERGY IN A CONDENSER. When a condenser is charged by a steady pressure, the energy stored up by it is equal to that taken up from the charging circuit.

The potential difference across the condenser plates begins with nothing, and ends with the p.d. of the ends of the circuit; its average value being thus half that of the charging pressure. Hence the energy absorbed from the circuit in charging is obtained by multiplying together the quantity Q and *half the charging pressure* V, which gives joules, for joules = coulombs × volts. If the capacity K (in farads) and V be given, Q may easily be found, for—

$$Q = KV.$$

Then the work expended (or energy absorbed) in charging the condenser, in foot-pounds,

$$= Q \times \frac{V}{2} \times \cdot 7373 \text{ (i.e., joules} \times \cdot 7373).$$

The useful energy in a condenser, viz., that which will appear on discharge, is, as already stated, equal to that absorbed in charging, i.e.—

$$= \frac{QV}{2} \text{ joules}$$

$$= \frac{KV^2}{2} \text{ joules (as } Q = KV)$$

$$= \frac{KV^2 \times \cdot 7373}{2} \text{ ft.-lbs.}$$

64. CONDENSERS IN PARALLEL AND IN SERIES. The condenser illustrated in Fig. 41 is what may be termed a single condenser, as it consists of but two sets of coatings connected to the two terminals outside. Sometimes a number of condensers are mounted in one box, and arrangements made for connecting them up in various combinations.

When condensers are joined in parallel each set of coatings is equal in area to the aggregate of the different coatings which are connected together. Hence, when a number of condensers are joined in parallel, the resultant capacity is equal to the sum of the capacities of the separate condensers.

When a number of separate condensers are connected in series, the reciprocal of the resultant capacity is equal to the sum of the reciprocals of the capacities of the separate condensers.

Ex. (*a*). If three condensers, having capacities of $\frac{1}{3}$, $\frac{1}{3}$ and $\frac{1}{2}$ of a microfarad respectively, be connected in parallel, the resultant capacity K will be—

$$K = \tfrac{1}{3} + \tfrac{1}{3} + \tfrac{1}{2} = \cdot 33 + \cdot 33 + \cdot 5$$
$$= 1 \cdot 16 \text{ mfd.}$$

Ex. (*b*). If the same condensers be joined in series, the resultant capacity K will be

$$\frac{1}{K} = \frac{3}{1} + \frac{3}{1} + \frac{2}{1} \quad \therefore K = \tfrac{1}{8} \text{ mfd.}$$

These methods of calculation should be compared with those employed with wires in series and parallel. They are similar to those used when we consider the combined conductances of the wires; capacities and conductances being added when they are respectively in parallel.

Just as the total pressure across a number of conductances in series is divided in inverse proportion of the conductances, so the total pressure across a number of condensers in series is divided in inverse proportion of the several capacities.

65. USES OF CONDENSERS. Condensers are indispensable as standards for measuring the capacity of electric lines, and for this purpose are built up (in the manner illustrated in Fig. 41) of a large number of sheets of tinfoil and mica mounted in a box with an ebonite top carrying the terminals. Fig. 44 gives an external view of one form of such a condenser. The brass plug is provided to short-circuit the condenser when not in use, or when the capacity has to be cut out of circuit.

An important application of the condenser in modern power practice is in the improvement of power-factor on a.c. systems. For convenience in manufacture, condensers for this purpose are often made of a long strip of suitable paper rolled up with two long thin strips of tinfoil, one on each side of the paper. This is electrically a similar arrangement to Fig. 41. The rolled-up combination is then hung in a metal tank which is filled with insulating oil, the oil impregnating the paper and greatly adding to its dielectric strength.

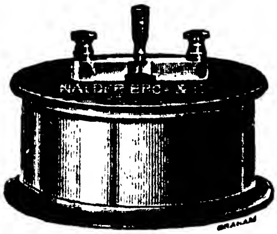


Fig. 44.—Standard Condenser.

66. CHARGE. To measure the charge, or quantity Q taken by a condenser **K** it would be joined up with a charge and discharge key k, as in Fig. 45. The key has two positions, one with the spring-lever pressing against a top contact d, and in the other, when depressed by the finger-tip, the lever is bent down to make contact with c. When so depressed the condenser is charged as described in §60. If the lever be now allowed to rise, it makes contact with d and the condenser discharges through **G**, the swing of whose pointer is proportional to Q. If it be desired to measure the quantity entering the condenser on charging as well as discharge then the connections would be as in Fig. 46, which depicts a different pattern of key, having a middle position i where it can rest out of contact with *c* or *d*, and therefore leaves the charged condenser insulated.

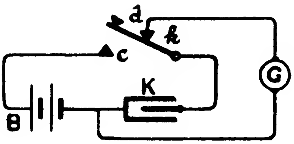


FIG. 45.

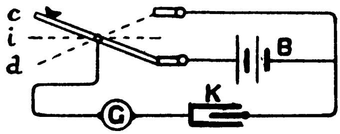


FIG. 46.

67. THE CHIEF EFFECTS OF A CURRENT are five in number—

(*a*) *Magnetic.* A current flowing along a conductor sets up a magnetic field around the conductor. If the conductor be straight, the field will consist of concentric circular lines of force (Fig. 47). If the conductor be coiled-up into a helix or solenoid, the field will be made

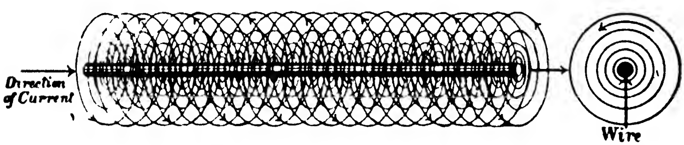


FIG. 47.—FIELD DUE TO A DIRECT CURRENT IN A STRAIGHT CONDUCTOR.

up of lines running more or less through the coil, and out at either end.

(*b*) *Heating and Luminous.* Whenever a current flows along a conductor, heat is developed in the conductor. As a rule, the heat generated is too little to be noticeable; but if the current be great, and the wire thin and of a metal of low conductivity, sufficient heat may be generated to make the wire red or white hot.

If the current be passed through a hermetically-sealed tube containing mercury vapour, the latter will be rendered brilliantly incandescent, although the temperature will not be very great. This is the principle of the *mercury-vapour lamp*.

If the two ends of a circuit having a sufficient p.d. be brought together and then slightly separated, an intense light will play in the gap thus introduced in the circuit. This light is due to the formation of the *electric arc*, and the colour of the light emitted depends to a great extent on the material composing the ends of the circuit between which the arc plays. If the extremities be of metal, a p.d. of about 10 volts will suffice to maintain the arc; but if of carbon, the p.d. must be about 40 volts. This is the principle of the *arc lamp*, in which carbon rods form the extremities of the circuit.

(*c*) *Chemical*. When a direct current of electricity is passed through certain chemical solutions, it splits them up into their constituents. This action is known as *electrolysis*, i.e. electric analysis. A *voltameter* is an instrument in which electrolysis may be performed, and in which the amount of such electro-chemical action may be accurately measured. And the amount of chemical action effected by the passage of a current through an *electrolyte* (solution which may be electrolyzed) in a given time, is directly proportional to the strength of the current.

Upon these three effects of a current, magnetic, thermal and chemical, most of the industrial applications of electricity are based. Motion, whether of signalling appliances or the distribution of motive power, depends upon the first, electric lighting in its various forms upon the second, and electro-plating, the storage of electrical energy and the production of many metals in a pure state upon the third.

(*d*) *Physiological*. The passage of a current through the body produces contraction of the muscles, and contraction of the capillary blood-vessels. If the pressure be high, or the resistance of the body low, the current may cause instant death from electric shock.

(*e*) *Radiant*. When electricity is passed through a vacuum tube, i.e. a tube which has been exhausted of air and hermetically sealed, the discharge will be luminous owing to the setting-up of *kathode rays*: and other rays besides these luminous ones, known as *X or Röntgen rays*, will emanate from the tube. A high and rapidly intermittent pressure—such as that from an induction coil or influence machine—is necessary for this effect; the electricity being led into and out from the tube by means of platinum *electrodes* or terminals.

X rays possess very peculiar properties. They are invisible, and yet will affect a photographic plate in much the same way as light. They will pass through solid bodies with more or less ease; it

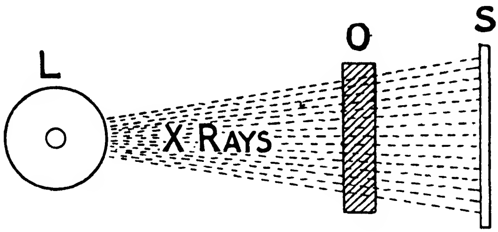


FIG. 48.—X RAYS AND FLUORESCENT SCREEN.

being a remarkable fact that most insulators offer little obstruction to their passage, whereas good conductors (metals) obstruct them in varying degree. Thus various bodies, liquids as well as solids, may be arranged in an order according to their degree of "transparency" to X rays. The rays, moreover, unlike ordinary currents of electricity, are not deflected by magnetic fields.

When, in a darkened room, the rays are allowed to impinge on a *fluorescent screen*,* they light it up; that is to say, they cause the surface of the screen to become luminous. On this fact (as well as on that previously mentioned, viz., the action on a photographic plate) depend a number of useful applications of X rays.

In Fig. 48, L is the vacuum tube or *X-ray lamp* as it is sometimes termed, and S the fluorescent screen; the rays being denoted by the dotted lines. If nothing be interposed between L and S, the latter will be uniformly lighted-up; but if an object O be placed between, an "image" will appear on the screen. If O be a plate or sheet of some given substance, the lighting of the screen will be

* Certain chemical salts have the power of absorbing light and of shining afterwards in the dark, this being due to their *fluorescent property*. When spread over a surface that is transparent to X rays, such as a sheet of cardboard the combination forms a *fluorescent surface* or *screen*.

more or less reduced according to the "transparency" of the substance. If the object be not homogeneous, those portions which obstruct the X rays most will show up dark on the screen. Thus if a man's body be interposed, the bones will show up faintly, while the metal parts of his braces, his buttons, his cash, and so forth will stand out very plainly. Metal objects placed between the leaves of a book held at O will be clearly indicated, a boot will show the nails (if any) used in its construction, the money in a purse will be shown up, and so on. If a photographic plate be substituted for S, a photo of the "image" may be secured.

The usefulness of X rays in surgery and in many other ways will readily be understood; and there are various other properties of the rays of which no mention can be made here.

We have dwelt at some length on the radiant effect of the electric current or discharge (although we shall not be further concerned with it in this book) as upon it depends a very important branch of electrical science. The results detailed above are, moreover, specially interesting; as they indicate the very close connection between electricity and light.

68. MAGNETIC EFFECTS. Because of the magnetic field set-up round a current carrying conductor, if the latter be placed above or below a magnetic needle and parallel with it, it will tend to turn the needle at right angles with itself. How far it succeeds in doing this will depend upon the strength of the current. If the current, and therefore the field, be strong, the conductor will pick up iron filings.

A *magnetic field* is any space filled with lines of magnetic force. We assume that these lines, when once set up by a steady direct current, do not move; but we suppose a "positive" and a "negative" direction along them, just as we speak of the "up" and "down" directions along a railway. The *positive direction along the lines of a magnetic field* is the direction in which a free N pole, if it were possible to get one, would travel; viz., from the N to the S pole of a magnet or solenoid, through the air outside.

We have then to ascertain by experiment the relation between the direction of current (conventionally assumed to be that in which metals are carried by the current in a voltameter) and the positive direction of the field. This relationship has been found to be quite a simple and definite one which is most clearly expressed in the two following rules.

Clock-face rule. Looking at the end of the conductor in the direction of the current, the positive direction round the field is the same as that in which the hands of a clock move, i.e. clockwise. The application of this rule is shown in Fig. 49 (where the current is coming to the observer and the field direction is counter-clockwise) ; and in Fig. 50, where the current is going from the observer and the direction is clockwise.

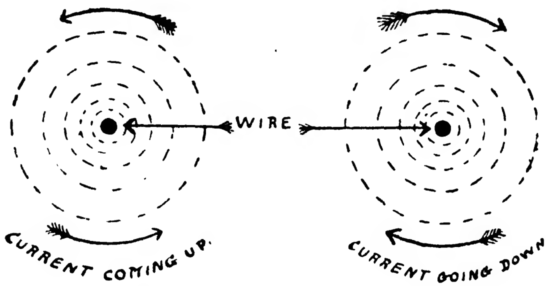
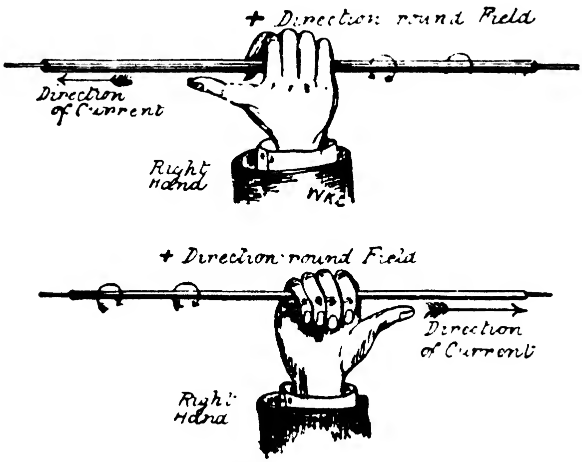


Fig. 49. Fig. 50.

Screw rule. *Associate the rotation and travel of a right-handed screw with, respectively, the + direction round the field, and the direction of the current, looking at the end of the conductor.* Thus, to drive the screw in it must be turned in a clockwise direction : if the current goes in, the field is in a clockwise direction. To bring the screw out it must be turned in a counter-clockwise direction : if the current be coming out, the field is in a counter-clockwise direction.

69. DIRECTION OF FIELD. The relation between the direction of a direct current in a conductor and the positive direction round its field can always be found from an application of the clock-face and screw rules already given, but the matter can be further explained by the following diagrams. They bring out clearly the fact that magnetic lines are always at right angles to the current producing them.

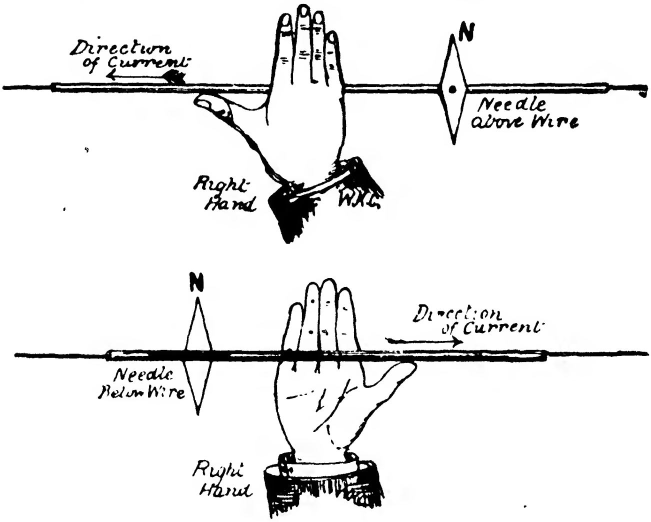
A convenient mode of remembering the relation between field and current, or, as we shall have to deal with next, between inducing field and induced current, is to utilize one's right hand. If the right hand be placed across the conductor, with the palm facing the conductor, and the outstretched thumb pointing in the direction of the current, then the fingers curled round the wire may be regarded as the lines of force, and they will denote the positive direction along the conductor's circular lines of force, as in Figs. 51 and 52.



FIGS. 51 AND 52.

From this it follows that if the right hand be placed across the conductor and on the same side of the conductor as a pivoted magnetic needle (which can be brought parallel to the conductor if necessary by the use of a magnet, should the conductor not be N and S, or nearly so) then the outstretched fingers will denote the direction in which the N pole of the needle will turn (Figs. 53 and 54). The N pole of the needle if free from all constraint would follow the direction of the lines of force, and in any case it does so, or attempts to do so. The S pole is urged in the opposite direction so that the combined pull and push turns or twists the needle until it comes to rest at right angles to the wire (if the current be very strong) or at something less than this if the field produced by the current is not sufficiently strong to turn it so much.

To find the direction of a direct current in a conductor, therefore, the conductor should be moved, if possible, into the magnetic meridian. A small compass needle should



Figs. 53 and 54.

be held above or below the conductor, and the direction in which the N pole of the needle is deflected would be noted. Then, by placing the right hand on the same side of the conductor as the needle, with the palm facing the conductor, and the fingers pointing in the direction of the deflection of the N pole of the needle, the direction of the current will be denoted by the outstretched thumb.

70. DIRECTION OF CURRENT. If a direct current be sent in one direction through (*a*) a helix of wire, (*b*) an incandescent lamp, and (*c*) a voltameter, and the magnetic field, light and metal deposited respectively be investigated, and then the direction of the current be reversed, it would be found that the N pole of the helix had changed to a S pole, the light from the lamp would be unaltered, and the metal would be deposited on the opposite end of the voltameter. Thus we get our idea of direction of a current from magnetic and electro-chemical effects. The fact that the lamp behaved in the same way with the current in either direction indicates that it could be used on direct or alternating currents equally well, provided the strength of the current remained unaltered.

Next, to get an idea of the meaning of strength of a current, if we double the current through the same circuit, the magnetic effect of the helix will be doubled, the heat in the lamp will be quadrupled, and the weight of metal deposited in the voltameter will be doubled. Thus a current-measuring instrument can be constructed by the helix and some means of ascertaining the magnetic effect it produces, while current strength can be defined by stating how much metal is deposited per second by what we decide to select as the unit of current.

71. POLARITY FINDING. When a current is derived from a battery near at hand, it is easy to ascertain which are the + and – wires.

Very often, however, the source of e.m.f. is at a distance. In such a case, assuming the wires at hand are connected with the distant source of e.m.f., there are various ways of finding out which is the + wire and which the –.

(*a*) Dip the ends of the wires—without allowing them to touch each other—into a glass of water. Minute bubbles of gas will immediately be given off at the extremity of the – wire.

If the circuit e.m.f. be low, it may be necessary to add something to the water to improve its conductance. A little salt or soda will do this.

(*b*) Moisten a strip of *pole-finding paper*, and lay the ends of the wires on it. The paper will then generally become discoloured where the – wire touches it. Sometimes, however, the discoloration denotes the + pole. Pole-finding paper is chemically prepared, and when connected in circuit becomes discoloured either at the – or + pole. The pole at which the discoloration will appear depends on the preparation of the paper. Thus most papers turn pink at the – pole, but some turn brown at the + pole.

(*c*) A similar principle is employed in the *pole-finder*, which consists of a tube filled with a liquid capable of electrolysis. A terminal is fitted at each end of the tube. and electrodes connected with them pass through into the liquid. When this apparatus is joined-up in circuit, the wire connected with the – terminal becomes coloured, the colour disappearing gradually after the current has been stopped.

(*d*) Provided the e.m.f. be not too great—say not exceeding 250 volts—a detector may be used, if it has been previously ascertained which direction of deflection corresponds with the + polarity of one of the terminals. In other words, supposing we knew beforehand that the right-hand terminal was + when the needle moved to the right, we should be enabled to say which wire was + and which –, on seeing the deflection of the needle.

This and similar methods which depend upon the magnetic effect of the current, must only be used with a very low voltage, unless the precaution be taken to insert sufficient resistance. This may be a lamp or wire resistance, capable of reducing the current to a safe amount for the circuit.

72. MAGNETS. A magnet is anything which has the power of attracting pieces of iron or steel, and of separating them from other loose bodies. There are two principal kinds, *permanent* and *electro*-magnets. The former are made of hardened steel and, when once magnetized, retain their power. The properties of the latter are due to the magnetic effect of the current. Electro-magnets are generally made by winding an insulated conductor around a soft iron core or centre. When electricity flows through the conductor the iron becomes magnetic, but loses most of its magnetism directly the current ceases. There need not necessarily be iron in an electro-magnet, but the addition of iron very greatly increases the magnetic effect. For instance, when a current flows through a conductor, that conductor becomes an electro-magnet throughout its entire length, for it is able to pick up iron filings if the current be great enough.

73. LINES OF FORCE. The power which a magnet possesses, of picking up pieces of iron and of acting upon another magnet, depends upon the existence of *lines of magnetic force*. In the case of a permanent magnet, these lines pass through the air from the N to the S pole, and through the substance of the magnet itself from the S to the N pole ; as shown in Figs. 55 and 56, where the arrows denote the + direction along the field. In the case of a straight current-carrying conductor, the lines of force arrange themselves in concentric circles about the conductor.

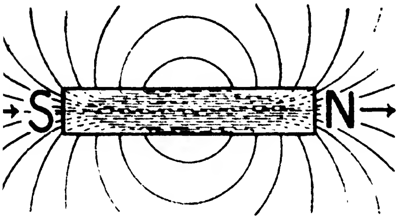


FIG. 55.—MAGNETIC FIELD OF A BAR MAGNET.

Lines of force are always continuous. Only those close to the magnets can be shown in this way in the figures, but the part omitted must be imagined.

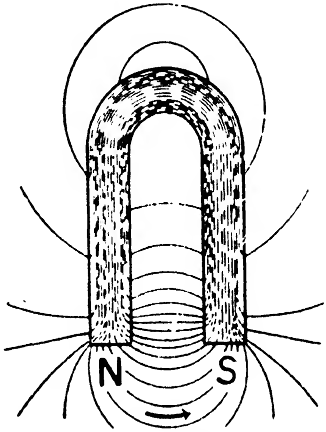


FIG. 56.—MAGNETIC FIELD OF A HORSESHOE MAGNET.

In the case of a helix or *solenoid*, the lines run more or less through the coil and out at each end (Fig. 57).

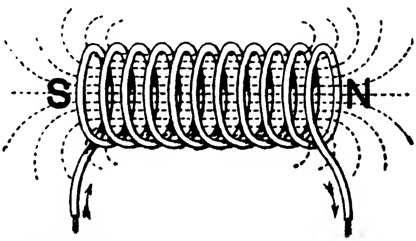


FIG. 57.—MAGNETIC FIELD OF A SOLENOID.

If there be iron in the electro-magnet, such as an iron bar in a coil of wire, more of the lines pass from end to end of the coil without leaking out at the sides, and their number is very much increased (Fig. 58).

The figures illustrating the magnetic fields of current-carrying conductors, and of permanent and electro-magnets, are only intended to give a rough idea of the general distribution of the lines. The actual number of lines is usually very much greater, and they extend over a larger area than is shown in these figures.

74. THEORY OF MAGNETISM. According to the generally-accepted theory, every molecule of iron or steel is a complete magnet with a N. and a S. pole. In the so-called unmagnetized condition of the metal, these magnetized molecules are so jumbled up as to complete their

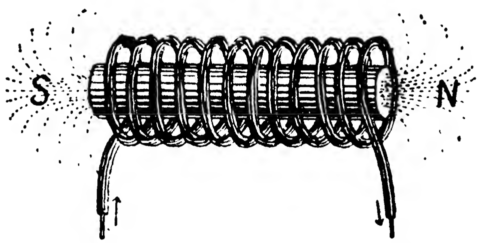


FIG. 58.—SIMPLE BAR ELECTRO-MAGNET.

Only a portion of each line of force is shown in the figure. The lines are continuous and form complete magnetic circuits.

magnetic circuits through one another: consequently no lines pass into the air, and there is no *free magnetism.* If lines of force, either from another magnet or due to a current in a conductor, be caused to pass through a piece of iron or steel, all the little magnetized molecules, previously jumbled up, will set themselves, more or less, in rows along the lines which are passing amongst them, with their N poles pointing in the + direction along the lines. The effect of this is to set up a free N pole at one end of the piece of iron or steel, and a free S pole at the other end. In this condition, the iron or steel is said to be *polarized.* In the case of hardened steel, the molecules when once set in line remain so, hence the permanent magnetization. With soft, i.e. annealed pure iron, on the other hand, directly the inducing lines of force are removed, the molecules, which may be supposed to be very much less closely packed together than the molecules of hardened steel, tend to jumble themselves up again, and wholly or partially succeed in so doing, according to the softness and quality of the iron. Hence the fact of the temporary magnetization of an electro-magnet.

In electrical-engineering work, without disputing the molecular theory, it is found more convenient to talk about good and bad *conductors of magnetic lines.* Thus iron and steel have very great magnetic conductance, whilst practically all other bodies, metal or otherwise, conduct magnetic lines rather badly.

75. STRAIGHT-CONDUCTOR ELECTRO-MAGNETS. It is possible to increase the magnetic effect of a current in a straight wire by the arrangements shown in Figs. 59 and 60. In the former figure, which may be said to show a straight-wire electro-magnet NS, NS, NS, is a length of split iron tube, such as a piece of gas-pipe cut in half longitudinally; NNN being the N pole, and SSS the S pole. In Fig. 60, representing a spiral or helical electro-magnet, NS is a helix of iron wire enclosing the conductor. In each case the circular lines pass through the iron, polarize it, and give us free poles, as shown. In the latter case, however, there would be some leakage of lines, and therefore polarity, at the beginning and end of each turn of the helix.

Such electro-magnets as in Figs. 59 and 60 are of little practical use, for the effect obtained is very slight, owing to the small number of magnetic lines which are available.

76. THE SOLENOID. The lines due to the current in a conductor are concentrated by coiling it up, the lines then altering their shape as shown in Fig. 57. Such an arrangement is termed a *solenoid.* A solenoid has N and S magnetic poles; and the result of introducing a bar of soft iron into the coil is to increase the magnetic effect very greatly. The lines due to the current pass through the iron, polarize it, and bring into action a number of lines of force due to the magnetized iron bar, in addition to those previously due to the current alone. Every line of force is separate and distinct from every other line of force, no matter how closely packed together they may be ; and every line forms a complete curve which varies in shape, according to circumstances : consequently a line of force has no ends. This we can understand with regard to the

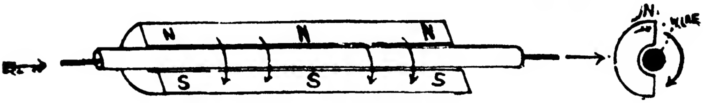


FIG. 59.—ELECTRO-MAGNET WITH STRAIGHT CONDUCTOR.

circular lines due to a current in a straight conductor ; but in the case of a bar magnet, or solenoid, some of the lines appear to lose themselves in the air and end there. This is not really the case, however ; each individual line completes its circuit, though we may not be able to trace out its whole path.

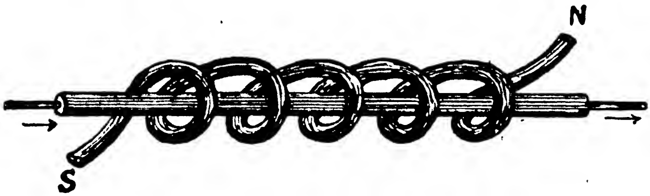


FIG. 60.—HELICAL ELECTRO-MAGNET.

In Fig. 57, representing the magnetic field of a solenoid, it will be noticed that some of the lines do not pass through the whole length of the coil, but leak out at the sides and curve round to complete their circuits. This is due to the tendency of every line of force to shorten itself as much as possible. Because of this leaking away, there are more lines passing through the middle of a solenoid than out at either end.

If a piece of iron be suspended over the mouth of a solenoid, as shown in Fig. 61, it will be forcibly drawn in to the middle of the coil ; the tendency being for the piece of iron to travel to that part of the field where the lines are most densely packed together. When the iron is outside the coil, a number of the lines of the solenoid lengthen themselves to pass through the iron, which is a very good magnetic conductor; and it is the tendency of the lines of force to shorten themselves that causes the iron to be drawn into the coil. This combination of the solenoid and movable core—generally termed the "plunger"—constitutes a practical form of electro-magnet; and the principle is made use of in a number of devices.

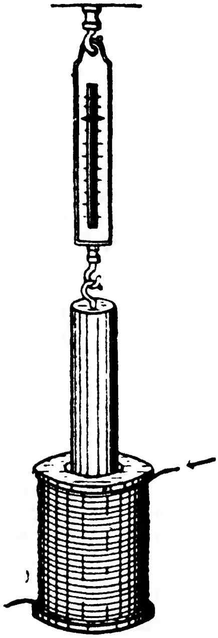


FIG. 61.—ATTRACTIVE FORCE OF A SOLENOID.

77. PRACTICAL TYPES OF ELECTRO-MAGNET.—

(*a*) *Bar.* (Fig. 58.)

(*b*) *Solenoid and Plunger.* (Fig. 61.)

(*c*) *Horseshoe.* Fig. 62 shows three kinds of horseshoe electro-magnet. In the first and second, the iron core of the magnet is in one piece; while in the third, the two cores are screwed at the back to a piece of iron Y termed the *yoke*. AAA are the armatures.

(*d*) *Horseshoe with Coil on Yoke.* (Fig. 63.) In this type there is only one coil, which is fixed on the middle part of the core (or the yoke).

(*e*) *Horseshoe with Coil on One Leg.* (Fig. 64.) One coil only is used also in this magnet, but it is placed on one of the legs instead of on the yoke. In each of these cases, however, more wire is used than with type (*c*); for to obtain a given number of lines with a given shape of iron core, and a given current, the number of turns must be nearly the same in each case; and in (*d*) and (*e*) the average length of each turn is greater.

(*f*) *Ironclad.* (Fig. 65.) In this magnet, the bobbin on which the wire is wound has the top cheek of brass or zinc, and the bottom one of iron. The core **N** and the top edge of the iron cylinder **SSS**, which fits over the coil and core, form the two poles of the magnet, while the iron

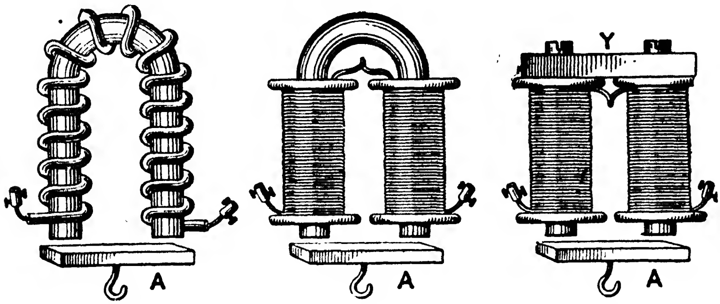


FIG. 62.—THREE KINDS OF HORSESHOE ELECTRO-MAGNET.

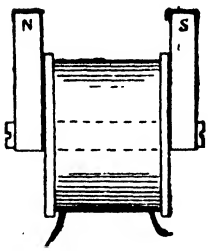


FIG. 63.—HORSESHOE ELECTRO-MAGNET WITH COIL ON YOKE.

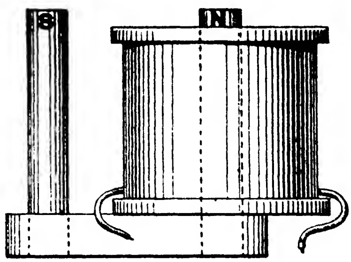


FIG. 64.—HORSESHOE ELECTRO-MAGNET WITH COIL ON ONE LEG.

coil-cheek at the bottom acts as the yoke. An appropriate armature for such a magnet would be a disc of soft iron. The ends of the coil pass through holes in the bottom cheek.

(*g*) *Annular Ironclad.* (Fig. 66.) This magnet is somewhat similar in principle to that just described. It is also similar to the straight-wire magnet shown in Fig. 59, except that it is circular in shape, and has a number of turns of wire. The inner face forms one pole and the outer face the other pole, while the flat washer acts as armature. The figure shows the coil and core in section, the front half being cut away.

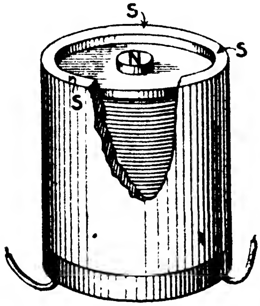


FIG. 65.—IRONCLAD ELECTRO-MAGNET.

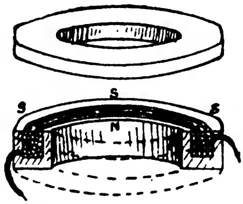


FIG. 66.—ANNULAR IRONCLAD ELECTRO-MAGNET.

(*h*) *Ironclad Plunger.* Fig. 67 illustrates a simple form of ironclad plunger magnet. Here PPP are the short fixed inner pole and iron case, and AAA the plunger armature.

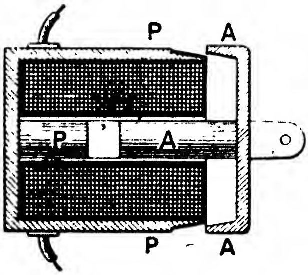


FIG. 67.—SIMPLE FORM OF PLUNGER MAGNET.

There are many modifications of each of the above types according to the circumstances under which the magnet is to be employed; and there are also various special forms. The solenoid and plunger magnet is utilized in a number of different ways, it being very extensively used in arc lamps, for instance.*

78. ELECTRO-MAGNETS. Fig. 68 is an early form of magnet for tilting the tube of an automatic *mercury-vapour lamp*; this operation being necessary as the lamp—when

* See the Author's *Electric Wiring, Fittings, Switches, and Lamps.*

"out"—is simply a vacuum tube with a small quantity of mercury at one end, the tube in its normal position being slightly inclined. When the tube is inclined in the opposite direction, the mercury runs right along and completes the circuit from end to end. As soon as this occurs, a current passes; and when the tube is allowed to return to its normal position, the small sparks formed at the breaks

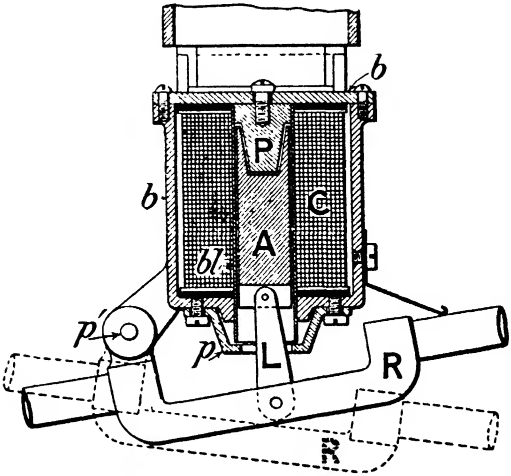


FIG. 68.—TILTING MAGNET FOR MERCURY-VAPOUR LAMP.

in the stream of mercury (owing to the presence of an inductance coil in the circuit) are sufficient to vaporize a small portion of the mercury and start the lamp working. The magnet consists of a coil **C** with yoke and enclosing cylinder *bb*, and circular pole-plate *p*, all of soft iron; a pole-piece **P** being fixed at the upper end of the hollow of the coil, which has a brass lining *bl*. **A** is the movable core or armature, this being linked by the brass piece **L** to the lamp-holder rod **R**, which is pivoted at *p′*.

It will be observed that the extremity of **P** and the upper end of **A** are so shaped that the former fits within the latter, though for reasons given later, they are prevented from coming into actual contact. When the current is passed round the coil or solenoid **C**, the armature **A**, which normally is held in the position shown by the weight of the lamp and its holder, is drawn slowly downwards, thus forcing the rod **R** into the position indicated by the dotted lines. When the current is stopped, the lamp rod returns *slowly* to its normal position, because **A** and *bl* fit fairly closely, and thus act as a dash-pot.

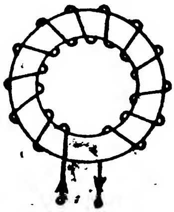


FIG. 69.

The reason **A** moves downwards when the coil is "energized," instead of remaining where it is, as one would at first expect, is as follows. From the shape of **P** and the end of **A** next to it, it will be evident that even if **A** move down so far that its extremity is level with the tip of **P**, the air gap introduced there would not be very great. On the other hand, such a movement would materially decrease the air gap between the lower end if **A** and the edge of the hole in *p* through which the link **L** passes. This is precisely why **A** does move downwards, the movement bringing the core into such a position that the total air gap is reduced as much as possible.

Some types of electro-magnet consist of a complete circuit of iron, more or less over-wound with insulated wire. Fig. 69 illustrates the principle of such a magnet. In this case, although the iron is magnetized, there is no external magnetism, as the lines of force complete their paths entirely in the iron. Magnets of this closed-magnetic-circuit type are used in alternating-current transformers, etc. The term "electro-magnet," however, generally implies the presence of free poles, and the consequent use of air as a portion of the path of the lines of force.

79. ACTION OF MAGNET ARMATURES. From the explanation of the action of magnets, the following general conclusion may be drawn.

A magnet armature tends to move into such a position that the air gap in the magnetic circuit of the magnet is reduced as much as possible. In other words, it tends to move into that portion of the air gap in which the lines would be most dense were the armature temporarily removed.

When the armature of a magnet is intended to be released directly the magnet is de-energized, it must be prevented from touching the iron of the poles. If this happens, the armature is liable to stick to the poles after the current has

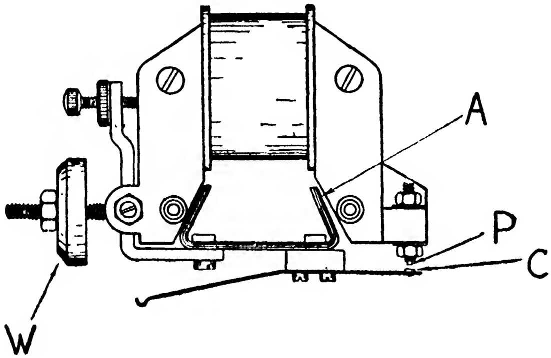


FIG. 70.—PROTECTIVE-RELAY MAGNET.
(*Metropolitan-Vickers.*)

been stopped, because of the residual magnetism in the magnet. To prevent this sticking, small brass studs (or similar devices) are fixed to the armature or poles to serve as "distance pieces"; but these need only project $\frac{1}{64}$th of an inch or so in small magnets.

A good example of this armature action is to be found in the relays used to make or break the trip circuits of large circuit-breakers in power stations. In Fig. 70 there is a laminated electro-magnet with a balanced armature **A** to which is fitted a contact-arm, carrying a contact **C**. The current which will attract the armature can be altered by adjusting a counterweight **W**. When a current in excess of that for which the relay is adjusted passes through the coil of the electro-magnet, the armature is lifted and **C** makes contact with the pin **P**. The coils are wound to carry a normal full load current of 5 amps.

80. POLARITY OF SOLENOIDS can be found from the clock-face or screw rules. A solenoid is simply a number of turns, each parallel to the others, so if we find the positive direction of the field for one turn, we have found it for all.

The lines of force instead of forming circles round each turn, coalesce or join together and form closed figures, which pass through the centre of the solenoid out at one

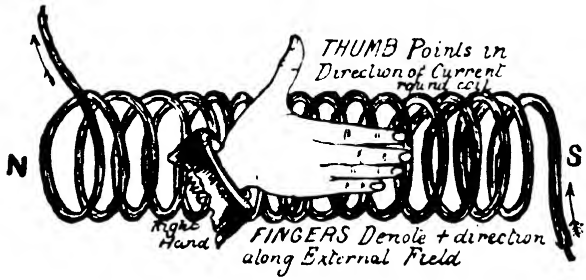


FIG. 71.

end, bend round, proceed outside through the air and return by another bending round to their original starting point.

In Fig. 53 the wire is shown horizontal. Turn the page sideways and the wire is vertical with the current flowing upwards. A N pole would be urged across the wire from left to right between the wire and the observer, as indicated by the outstretched fingers of the right hand. Such a wire might be any one of those in Fig. 71, where the current is flowing upwards on the portion of each turn nearer the observer. Hence the positive direction is from left to right outside the solenoid, and necessarily from right to left inside the solenoid. If the N pole of the solenoidal winding is what is wanted, then all that has to be remembered is that the N pole end will be that from which a free N pole would proceed outside the solenoid, being repelled, and the S pole is that to which it would be attracted.

A horseshoe solenoidal magnet is simply a straight solenoid bent over in the same way as a sheet of paper is folded in two. It may be manufactured more simply by having the two halves separately wound. A horseshoe electro-magnet when looked at end-on to the poles presents the view of two circles. Obviously the winding on each

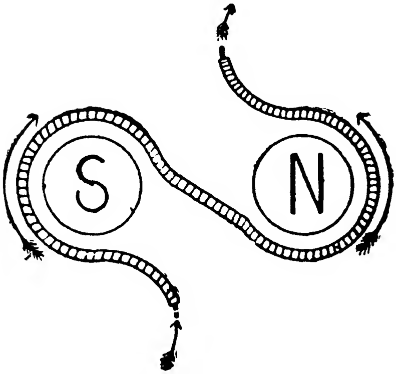


FIG. 72.

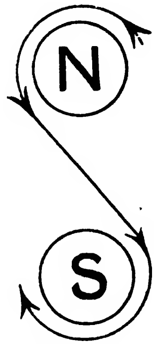


FIG. 73.

pole must be in reverse directions ; or if wound the same way the connections must be such that the current flows in opposite directions in the windings on the two limbs. This is indicated in Fig. 72. If one placed one's right hand with the palm against the wire on the right-hand side where the curved arrow points upward, the curled fingers round that wire would point towards the observer on the left-hand or inside of the wire. This indicates that the free **N** pole would move upwards from the paper and therefore that the pole would be of **N** polarity.

In writing a capital *S* one generally commences at the top and finishes at the bottom, as indicated by the arrow-heads in Fig. 73. If we imagine a magnetic pole at each end of the *S* the arrow-heads indicate the direction of a current which will give a **N** pole at the top and a **S** pole at the bottom. We can remember that the **N** pole is at the top, as in writing the *S* we move downwards, and this is the direction in which a free **N** pole would move, i.e. from the **N** pole to the **S** pole.

A form of electro-magnet which was formerly used for dynamos is shown in Fig. 74. The coils were wound so that two *N* poles, say, were at the top, and the two *S* poles at the bottom. As a result of this, *consequent poles* were formed at **NN** and **SS** and the magnetic lines streamed

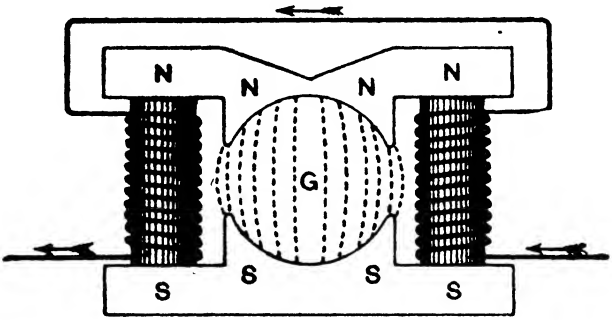


FIG. 74.—CONSEQUENT-POLE FIELD-MAGNET.

across the gap **G**. When an armature with its soft iron core was put into position the distribution of the lines of the field was considerably altered, and their number very much increased.

81. FIELD-MAGNETS. Electro-magnets for dynamo field-magnets have taken all sorts of shapes. One of the earliest is shown in Fig. 75, where the black represents the section of a coil, which cannot be indicated more definitely in the size of the illustration. The poles were at the bottom and kept off a bed-plate by blocks of non-magnetic material. Alternative methods were to turn the magnet upwards or sideways. One of the most curious forms of electro-magnet ever constructed and actually used is that of Fig. 76, which comprised two hollow shells, forming the poles, and upon the barrel portions of which coils were wound. The outer flanges were tied together and the magnetic circuit closed, or rather a return path provided, by a number of iron rods spaced at intervals round the circumference. This was the magnetic system of one of the most successful arc lighting machines in the early pioneering days of electrical engineering.

82. ALTERNATING-CURRENT MAGNETS. If an alternating current be sent round a coil on a solid iron core, the latter will become very hot and comparatively slightly magnetized.

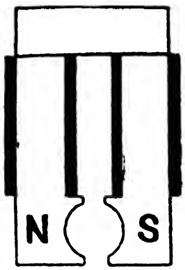


FIG. 75.—EDISON FIELD-MAGNET.

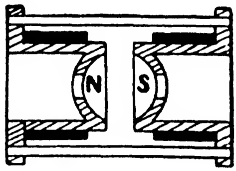


FIG. 76.—THOMSON-HOUSTON ARC-LIGHTER FIELD-MAGNET.

When an alternating current flows round a circuit, a secondary alternating current is induced in a neighbouring circuit, or in any neighbouring piece of metal.

Thus if an alternating current be sent round the coils of a solid-core electro-magnet, the core will act as a neighbouring conductor; and secondary currents (or, as they are called in this case, *eddy currents*) will be continuously set up therein. These induced currents absorb a good deal of energy, and would heat the core so much that the insulation of the coils would be burnt away.

An electro-magnet intended for use with alternating currents should be made of the best annealed iron, and carefully laminated; each separate sheet of iron being separated from its neighbours by a thin coating of varnish or other insulation. This lamination of the core stops the circulation of eddy currents, and the resultant waste of energy, which would show itself in the form of heat; while the iron, being laminated and of good quality, is more susceptible to the rapid reversals of the magnetic field.

In short, an alternating-current magnet with a solid core would be much less effective than one with a laminated core, for three reasons: (*a*) the waste of energy in heat; (*b*) the higher temperature (the susceptibility of iron to magnetization decreases as the temperature increases, as proof of which is the fact that a magnet will not attract a red-hot piece of iron); (*c*) the demagnetizing effect of the eddy currents, which act in opposition to the main current.

Badly-designed alternating-current magnets, transformers, etc., "hum" loudly when the current is passing. This is chiefly due to imperfect clamping together of the iron sheets, and also to the continuous movement of the molecules of the iron core. Where alternating current is available a "buzzer" may replace an ordinary bell and battery. It emits a loud note when the current flows through it, and as it has no working parts it always remains in good order.

83. THICK AND THIN WIRE COILS. The strength of an electro-magnet depends, roughly speaking, upon two things—the *number of turns* of wire on its coils and the *current*; that is to say, upon the **ampere-turns** of the coil. Thus a magnet wound with many turns of fine wire with a weak current passing through it, may pull its armature as strongly as a magnet wound with comparatively few turns of thick wire carrying a strong current.

Instruments for long distance working, where the current is weakened by the high resistance of the circuit, are wound with many turns of fine wire. On the other hand, apparatus for short-distance working, where the current is stronger and the circuit is of low resistance, have comparatively short lengths of thick wire on their coils. Electric bell relays, for instance, are required to work with weak currents, and are wound with many turns of fine wire.

With a given current, the greater the number of turns of wire on its coils, the greater will be the pull of the magnet; provided the iron core be not already magnetized to *saturation*. For with a given thickness of core there is a limit to the amount of magnetism that can be developed in it; this limit depending on the quality of the iron employed. If we take any given bobbin filled with a certain number of turns of comparatively thick wire, in order to get a greater number of turns on to the same bobbin, we must wind it with finer wire. There is a limit to the size of bobbin in each particular case, and, having fixed on this limit, we choose the largest possible size of wire which will fill the bobbin, and at the same time give the required number of turns. The finer the wire, the greater the resistance. Fine wire is not used because there is any particular virtue in it, but because it is necessary sometimes in order to get the proper number of turns on the coil.

It is a puzzle to some students that an instrument (a galvanometer, for instance) with high resistance should, generally speaking, be more sensitive to weak currents than one with a low resistance. The resistance is not there because it is wanted, but because it is the result of the use of a great length of fine wire in order to get the desired number of turns.

In some cases it is necessary to lessen the inductance of a magnet, and this may be done by joining its coils in parallel, instead of in series. When so doing, care must be taken to see that the current flows round the coils in opposite directions, so as to give the proper polarities.

84. HEATING OF COILS. In most cases the calculation of the winding for an electro-magnet starts with the fact that a given number of *ampere-turns* is to be produced Also the maximum size of the coil has usually been settled beforehand, and it is generally advisable to make the coil smaller than this if possible. In some cases the p.d. is fixed, in others the current, and in others the resistance.

In all cases care has to be taken that the coil will not heat-up unduly under the passage of the current. On the other hand—especially with large magnets—it is essential, in order to save expense, that the conductor should not be of much greater cross-section than is absolutely necessary to enable it to carry its current without overheating.

In regard to the heating of coils, the size of conductor to carry any given current depends primarily on the length of time the current passes, and also on the number of layers on the coil. Thus a coil which has to carry a certain current for hours at a stretch must be wound with thicker wire than one which is only required to carry the same current for short intervals of time: and a coil with few layers of conductor will heat-up less readily than one with a large number of layers, other things being equal. The facilities afforded a coil for getting rid of its heat must also be taken into consideration; these depending on the way it is mounted and on its surroundings. Thus a coil round which the air can circulate freely will part with its heat much more freely than one which is more or less enclosed.

85. MAGNET-COILS. It is proposed to deal only with direct currents; and to consider briefly the simpler cases.

The size of the core round which the coil is to be placed is generally determined beforehand; this depending, as explained in Chapter VI, on the total flux F required, and on the flux-density B to which it is decided to magnetize the core. Then, knowing the permeability μ of the core material at the given value of B, the requisite value of the magnetizing force H can be readily determined, as $\mathsf{H} = \frac{\mathsf{B}}{\mu}$.

If H be the magnetizing force required, and l the length of the coil in centimetres, the number of ampere-turns (CN) necessary will be given by the formula—

$$CN = 0{\cdot}8 \times l \times \mathsf{H} \qquad (1)$$

In the quantity CN above, C stands for the current, and

N for the number of turns. In the following examples we shall assume that the number of ampere-turns for the coil—wherever they are in question—has been settled already.

The value of **H** for a coil of a given length depends simply upon its ampere-turns, and is quite independent of its diameter. Thus, with a given core, there is little or no advantage in making the coil of larger size than will just fit the core; while conversely, it does not matter if the coil fits the core so loosely as to leave an air gap between. This is often done in the field-magnets of electric generators and in transformers, the air which passes between the core and the coil serving to dissipate the heat generated.

It will be evident, however—especially in the case of fine-wire coils with a great number of turns—that it is advisable to keep the internal and external diameters of the coil as small as possible; as any increase therein increases the *average length of the turns*, and consequently the total resistance of the coil. If, with a given size of wire, the p.d. were fixed, any increase in the average length of the turns, i.e. in the total resistance of the coil, would decrease the ampere-turns. Also, with a fixed p.d., the ampere-turns of a coil could not be increased by adding to the number of turns; for the resistance would be increased at the same rate, and the current consequently diminished, so that the ampere-turns would remain unaltered.

Each successive layer of turns on a coil is greater in diameter, and therefore contains a greater length of wire, than the layer underneath it; and its resistance consequently is greater. The average resistance of the layers (or turns) of wire on a coil is that of the middle layer (or turn); and this resistance, multiplied by the number of layers (or turns), will give the total resistance of the coil.

86. CALCULATION OF WINDINGS. We will now consider a few simple cases relating to coils.

(CASE A.) *To find the approximate length of wire for—*

and the approximate resistance of—a coil; given the size of the bobbin or holder on which it is to be wound, and the size of the wire.

If with a given bobbin (Fig. 77), D_1 be the outside diameter of the innermost layer of wire, D_2 the outside diameter to which the coil is to be wound (i.e. the diameter of the outer layer), d' the diameter of the wire including its covering, D_3 the depth of the winding, and L the length

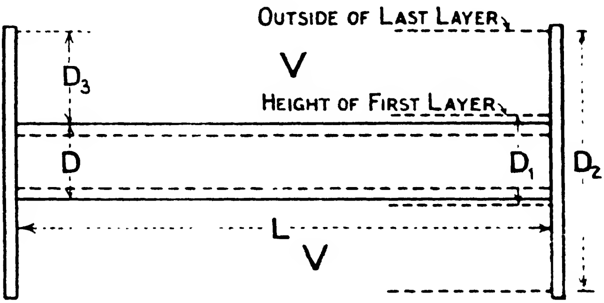


FIG 77.—COIL BOBBIN DIAGRAM.

between the cheeks of the bobbin (all in inches): the length l of the wire for the coil will be approximately as follows—

$$l = \pi \frac{D_2 + D_1 - 2d'}{2} \times \frac{L}{d'} \times \frac{D_3}{d'} \qquad \text{(II)}$$

In the above equation $\frac{D_2 + D_1 - 2d'}{2}$ is got from $\frac{D_2 - d' + D_1 - d'}{2}$, and is obviously the *average diameter of the layers or turns.* Multiplying this by π gives us the average length (l') of the turns. $\frac{L}{d'}$ is clearly the number of turns in a row or per layer, while $\frac{D_3}{d'}$ is the number of layers.

Knowing the size of the conductor, and having found its length in inches, this length should be multiplied by the resistance per inch of the conductor (which may be got from any Wire Gauge Table*), to get the approximate resistance of the coil.

If D_1, D_2, D_3 and d' be measured in cms., the resistance of the wire must be found for the same length.

In the above case, and in *all* cases where round wire is used, it must be assumed that each succeeding layer of turns rests on the top of the layer underneath. This is so for the reason that each turn is bound to cross one of the turns of the layer beneath it; so that an upper layer does not fit into the little grooves left between the neighbouring turns of the layer below it.

(CASE B.) *To find the approximate size and length of wire for, and the number of turns that will go on a bobbin of a given size, knowing the resistance which the coil is to have.*

Referring to Fig. 77, the space or volume V available for the winding is given by the formula—

$$V = \pi L \left[\left(\frac{D_2}{2}\right)^2 - \left(\frac{D}{2}\right)^2 \right] \qquad \text{(III)}$$

Now each turn and each layer takes up practically as much space as if the wire were square in section, as explained above. This being so, it should be evident that we may look upon the diameter d' of the wire, including its covering, as the side of a square, the area of which will be d'^2. Then, if we call l the total length of the wire on the coil—

$$l \times d'^2 = V. \qquad \text{(IV)}$$

By §39—

$$R = \frac{l}{\frac{\pi}{4}d^2}\rho \qquad \text{(V)}$$

Where R is the resistance of a wire, l its length, $\frac{\pi}{4}d^2$ its cross-sectional area, and ρ its specific resistance,

Then
$$\frac{R\pi}{\rho 4}d^2 = l \quad \text{and—} \quad d^2 = \frac{4l\rho}{R\pi} \qquad \text{(VI)}$$

* See the Author's *Electric Wiring Tables.*

From (IV)— $d'^2 = \frac{V}{l}$ (VII)

Then, substituting d'^2 for d^2 $\frac{4l\rho}{R\pi} = \frac{V}{l}$

$\therefore \quad l^2 = \frac{\pi R V}{4\rho}$ So that— $l = \sqrt{\frac{\pi R V}{4\rho}}$ * (VIII)

Thus by equation (III) we find the space available for the coil. By (VIII)—knowing the required resistance—the length of the wire may be calculated. By (VII) we can then find the outside diameter (including the covering) of the wire, and thus—by making suitable allowance—its naked diameter. Its size in S.W.G. (Standard Wire Gauge) may then be got from a Wire Gauge Table. Knowing the total length of wire (l) in the coil, the number of turns may be determined by dividing l by the average length of the turns, as ascertained by the formula $\pi \frac{D_2 + D_1 - 2d'}{2}$ previously given.

Or the number of turns may be found as in the following case—

(Case C.) *To find the approximate number of turns of wire on a coil; given the outside diameter of the wire (i.e. including its covering), and the length and depth of the winding space in the bobbin.*

Let d' be the outside diameter of the wire, L and D_3 the length and depth respectively of the winding space in the bobbin, L' the number of layers, t the number of turns in one layer, and N the total number of turns; then—

$$t = \frac{L}{d'} \text{ and } L' = \frac{D_3}{d'} \qquad \text{(IX)}$$

* The calculation is simplified as shown by assuming that d'^2 is practically equal to d^2; but for a correct result, the thickness of the covering must be taken into account. The smaller the wire the greater the necessity for this. Thus to get a correct result in (VIII), we must multiply V by the ratio $\frac{d^2}{d'^2}$.

Thus $tL' = \frac{LD_3}{d'^2}$ But— $tL' = N$

$$\therefore \quad N = \frac{LD_3}{d'^2} \qquad \text{(X)}$$

(Case D.) *To find the size of wire for a given coil; given the p.d. to be applied, the number of ampere-turns required, and the size of the bobbin.*

Knowing the size of the bobbin we know also D and D_2. Then the average length of the turns (l') may be got from the following formula—

$$l' = \pi\left(\frac{D_2 + D}{2}\right) \qquad \text{(XI)}$$

If r stands for the average resistance per turn, E for the p.d., and CN for the ampere-turns—

$$r = \frac{E}{CN} \qquad \text{(XII)}$$

Having thus found the average length and average resistance per turn, the cross-sectional area a of the wire will be—

$$a = \frac{l'\rho}{r} \qquad \text{(XIII)}$$

It should be noted that with a fixed p.d., fixed number of ampere-turns, and fixed size of bobbin, there is only one size of wire that will suit. And if the gauge should be too small or too large for the current to be carried, the size of bobbin must be altered.

(Case E.) *To calculate the size of wire and size of coil necessary; given the ampere-turns required, the average length of each turn, and the pressure to be applied at the ends of the coil.*

If CN be the ampere-turns required, l' the average length of one turn in inches, E the p.d. to be applied to the end of the coil, and a the area of the wire in square inches, then—

$$a = \frac{0{\cdot}00000063\,CNl'}{E} \qquad \text{(XIV)}$$

The derivation of the above formula is as follows. To start with—

$$R = \frac{\rho \times l' \times 2{\cdot}54 \times N}{10^6 \times a \times 6{\cdot}45} \qquad \text{(XV)}$$

Here l' is multiplied by 2·54 to reduce it to cms. because ρ is the value for a cm. cube. For a similar reason, a is multiplied by 6·45 to bring it to sq. cms.; and the whole is divided by 10^6 (i.e. one million) to bring it from microhms to ohms, ρ being in the former unit.

Proceeding— As $E = CR$, and $\rho =$ (approx.) 1·6

$$E = \frac{1{\cdot}6 \times 2{\cdot}54 \times l'CN}{10^6 \times 6{\cdot}45 \times a}$$

$$\therefore \qquad a = \frac{0{\cdot}00000063\, l'CN}{E} \qquad \text{(XIV)}$$

Having found the area a of the wire, and settled the current C which it may be allowed to carry, the number of turns N on the coil will be got by dividing the ampere-turns (CN) by this current.

D would generally be fixed, as it involves the thickness of the core. Then, knowing l', D_2 can be got from formula (XI).

Thus $$\frac{\pi D_2}{2} = l' - \frac{\pi D}{2} \qquad \text{(XVI)}$$

Finally, from (X) and Fig. 77, L may be determined as follows—

$$N = \frac{L}{d'} \times \frac{D_3}{d'} = \frac{L}{d'^2} \times \left(\frac{D_2 - D}{2}\right)$$

$$\therefore \qquad L = \frac{2\,N\,d'_2}{D_2 - D} \qquad \text{(XVII)}$$

(Case F.) *To find the approximate weight, size, length, and resistance of copper wire necessary to give a certain number of ampere-turns at a stated voltage; when wound on a bobbin of given dimensions.*

(*a*) First find—by formula (III)—the space or volume V to be occupied by the coil.

(*b*) Remembering that the wire is circular in section, while the space it takes up in the coil is equivalent to a square whose side is equal to its diameter ; whatever be the size of the wire, and neglecting the space taken up by its insulating covering, the proportion of V filled up with copper (which we will call V') will be approximately as follows—

$$V' = \frac{V \times \frac{\pi}{4} d^2}{d^2} = \frac{\pi V}{4} \qquad \text{(XVIII)}$$

Here $\frac{\pi}{4} d^2$ is the cross-sectional area of, and d^2 the space taken up by, a round wire of diameter d.

(*c*) Given that copper weighs 555 lbs. per cubic ft., the weight of copper W that the bobbin will hold will be—

$$W = V' \times 555 \text{ lbs.} \qquad \text{(XIX)}$$

V' being expressed in cubic feet.

(*d*) If W be the weight of copper on the coil, this will be equivalent to the product of the cross-sectional area (in square feet) and the length (in feet) of the wire, multiplied by 555.

Thus $$W = \frac{\pi}{4} d^2 \text{ (in square feet)} \times l \text{ (in feet)} \times 555.$$

Hence $$\frac{\pi}{4} d^2 \times 144 \text{ (area in square ins.)} = \frac{144\ W}{l \text{ (feet)} \times 555} \qquad \text{(XX)}$$

Multiplying the result by 144 brings the area to square inches, and the actual size in S.W.G. can then be got from a Wire Gauge Table.

In the present case, however, we have not yet found l.

(*e*) a in (XIV) and $\frac{\pi}{4} d^2$ in (XX) both stand for the area of the wire; therefore, combining these two equations, we may write—

$$\frac{0\cdot00000063\,CNl'}{E} = \frac{144\ W}{l \times 555}$$

$$l = \frac{W \times 144\,E}{0\cdot00035\,CNl'}$$

$$= \frac{412000\,WE}{CNl'} \qquad \text{(XXI)}$$

We have already found W by (XIX), and $l' = \frac{\pi}{2}(D_2 + D_1 - 2d)$.

D_2, D_1, E and CN being known, l, the length of the wire, can then be calculated.

(*f*) Having found l, we can get the area and size of the wire as described in (*d*).

(*g*) Having found the weight, size, and length of the wire, it now only remains to determine its resistance. This—knowing the area and length—can be got from a Wire Gauge Table giving the resistance of a certain length of the given size. Or it may be found by (V).

Many of the workings given in this paragraph are more or less original, and some are only very approximate. Nevertheless, they will serve to give the student ideas as to how such calculations should be dealt with; and it is with this end in view that they are given in detail.

In some instances, the required values may be arrived at in other ways, and in all cases the conditions may be varied. In practice, of course, the engineer often works to a formula the derivation of which may not be clear to him, but which he knows to be more or less reliable.

QUESTIONS

1. How would you prove experimentally that a static charge of electricity resides on the surface of a body only, and how could you determine whether the static charge on a body is positive or negative?

2. Explain what is meant by electrostatic induction, and describe in general terms its effects on the working of electric lines.

3. What is a condenser, and to what uses is it applied in practical electrical engineering work ?

4. Explain the construction and action of a simple condenser, and define microfarad, capacity, and dielectric.

5. If we connect a condenser in circuit with a galvanometer and battery, then at the moment the latter is joined up a momentary deflection of the needle will be produced, the needle then returning to zero. Why is this the case ?

6. Sketch the connections for the experiment of charging a condenser from a battery and discharging it through a galvanometer. Make a second sketch showing the change necessary if the galvanometer is to show both the charging and the discharging current.

7. You have to make a condenser of about half a microfarad capacity. Explain how you would do it.

8. A condenser of six microfarads capacity is joined in series to a condenser of three microfarads capacity. What is the capacity of the combination ? *Ans.* 2 mfd.

9. State the laws connecting the combined capacity of several condensers arranged (*a*) in parallel, and (*b*) in series, with the separate capacities of the condensers. Write down a list of all the capacities it is possible to obtain with three condensers of 1, 2 and 3 microfarads respectively. *Ans.* $\frac{6}{11}$, $\frac{2}{3}$, $\frac{3}{4}$, $\frac{5}{6}$, 1, $1\frac{1}{5}$, $1\frac{1}{3}$, $1\frac{1}{2}$, 2, $2\frac{1}{5}$, $2\frac{3}{4}$, 3, $3\frac{2}{3}$, 4, 5, and 6 mfds.

10. A condenser of 30 mfds. capacity is connected in series with a second condenser, and it is found that the capacity of the combination is 12 mfds. What is the capacity of the second condenser. *Ans.* 20 mfds.

11. A condenser of 10 mfds. capacity is fully charged and then connected in parallel to a second condenser of unknown capacity. It is found that two-thirds of the charge has been lost. What is the capacity of the second condenser. *Ans.* 20 mfds.

12. A concentric main has a capacity of 3 mfds. What is the work stored in it, in ergs, if the inner and outer conductors are charged to a potential difference of 10,000 volts ? *Ans.* $Q = \cdot 03$ $\therefore Q \times \frac{1}{2} v = 150$ joules $= 1{,}500{,}000{,}000$ ergs.

13. A condenser having a capacity of 2 mfd. is connected to two terminals maintained at 2,000 volts. How much work is taken from the terminals, and how much can be got out of the condenser again ? *Ans.* Taken and got out $Q \times V/2 = 4$ joules.

Note to Question 13.—If 2,000 volts were suddenly connected to the terminals of a condenser without any resistance in circuit, the current would be infinite. At that moment there would be no back e.m.f., and without resistance in circuit there would be nothing to limit the current. In practice there must be resistance, and the p.d. on the battery terminals drops for an instant at the moment when an empty condenser is connected to them. As the condenser becomes charged, the back e.m.f. rises until the condenser is full, when its p.d. is equal to the e.m.f.

14. An air condenser has 0·001 mfd. capacity. What would be the capacity if the space between the plates were filled with paraffin

wax ? *Ans.* Since s.i.c. of the wax is 2·3 the capacity would be 0·0023 mfd.

15. What do you mean by the dielectric strength and the specific inductive capacity of an insulator ? Show how the relative capacity for storing energy depends upon the above quantities in the case of two plate condensers, one having air and the other glass as dielectric, but otherwise the same as regards dimensions ?

16. State the several phenomena which indicate that a current of electricity is passing through a conducting wire or cable. On what grounds are we justified in saying that the current flows in one direction or the other ?

17. A magnetic needle, when placed parallel to a wire through which a current is flowing, turns at right angles to the latter, explain why this is the case.

18. Knowing the direction of the current in a conductor, how would you deduce therefrom the direction of the field ?

19. Describe how you would use a magnetic needle or compass to detect which way a current was flowing in a wire in the following cases: (1) When the wire is running along horizontally under a ceiling; (2) when a wire is running horizontally on the surface of a wall; (3) when a wire is running vertically on the surface of a wall. Draw up a set of simple rules for the three cases.

20. Describe, with sketch, an arrangement for showing the rotation, around the pole of a magnet, of a conductor carrying a direct current.

21. How do you picture to yourself the change which occurs in the case of an electro-magnet when current is turned on ?

22. What is meant by the term "a line of magnetic force" ? How can the lines of force of an ordinary steel bar magnet be delineated ? Sketch the form they assume in the case of a bar and a horseshoe magnet respectively.

23. How could you magnetize a steel corkscrew by means of the current in a straight wire ?

24. Under what conditions is a bar of iron or steel said to have "free magnetism" ?

25. Give sketches of the magnetic fields due respectively to the current in (i) a straight wire, (ii) a solenoid, (iii) a solenoid with an iron core, and (iv) a semicircular solenoid.

26. Draw a solenoid showing roughly the lines of force before and after the introduction of a soft iron core.

27. Explain the distribution of lines of force in a current-carrying solenoid, and say how and why the introduction of an iron core alters that distribution.

28. Show by a diagram how you would connect the two coils on the legs of a horse shoe electro-magnet, indicating the direction of the current in the windings and the resulting polarity.

29. Why does an electro-magnet pull so much less if you take out the iron core and replace it with a brass one ? Upon what factors does the strength of an electro-magnet depend ?

30. Explain the difference between bar and horseshoe electro-magnets. Name any application, and say which you think is the most convenient kind for that purpose, and why.

31. Give a concise list, with sketches, of the principal types of electro-magnet. Draw some form not shown in this book.

32. Give sketches of two kinds of ironclad electro-magnet, showing clearly the direction of the current and of the field.

33. An electro-magnet is required to work quickly, and to let go the armature instantly on the cessation of the current. How could this result be obtained ?

34. If two similar iron bars are put together inside a solenoid, what is the effect on them (1) when the bars are placed end to end ; (2) when they lie side by side ?

35. Mention a type of electro-magnetic apparatus in which there are magnetic lines of force, but no poles.

36. What difference, if any, should be made in the form of two electro-magnets, one of which is to have a long air-gap in its magnetic circuit, and the other a short air-gap ?

37. Supposing you had to make two similarly shaped electro-magnets, one for use with direct current, and the other for alternating current, would you construct them the same way or not ? Give reasons and sketches.

38. Why would an alternating-current magnet with a solid core be less efficient than if it had a laminated one ?

39. What is an electro-magnet ? In what way does its magnetism depend on its core, and in what way upon its coil ? What are the reasons which determine in any case whether the coil should consist of few turns of thick wire, or many turns of thin wire ?

40. State fully the qualities required in iron for electro-magnets. If a low e.m.f. were provided, should a thick or thin wire be used for winding an electro-magnet, the remainder of the circuit being of negligible resistance ? Give a proof of, and reason for, your answer.

41. What do you understand by the saturation of an electro-magnet ? How does this phenomenon affect the size of core for a given number of turns and current ?

42. What rules can you give about winding electro-magnets ? What are the circumstances that determine the selection of any particular size of wire for the coil ?

43. Having given the dimensions of an electro-magnet bobbin, how would you calculate the length of wire of a given diameter (including the silk covering) that could be wound on the same ?

44. An electro-magnet bobbin, 2 in. long, 1 in. external and $\frac{1}{4}$-in. internal diameter, is to be filled with wire 20 mils. in diameter. What length of wire will be required ? *Ans.* 102 yds.

45. Give some instances where permanent magnets are used for practical and scientific purposes. State for each case whether it is more important to have a strong magnet which may lose a small fraction of its magnetism with time, or a weak magnet which will lose practically none.

CHAPTER IV

INDUCED E.M.F.'S ; SELF AND MUTUAL INDUCTION

87. INDUCTION OF CURRENTS. It has been shown that when electricity flows through a conductor, circular lines of force are set up round the conductor.

If we take a straight conductor forming part of a closed circuit, and bring it into an independent magnetic field, so that it moves or cuts across the lines of force, a momentary current will be induced in the conductor. And when it is withdrawn from the field a second momentary current will be induced, in the *opposite* direction to the first induced current.

Strictly speaking, of course, it is electromotive force which is induced in the conductor, this giving rise to a current if the conductor form part of a closed circuit.

The lines of force round a current-carrying conductor remain unaltered so long as the current is steady. The induced e.m.f. in a conductor moving in a uniform magnetic field or cutting lines of force, remains unaltered so long as the motion continues at a uniform rate, or the lines of force cut per second do not vary. The induced e.m.f. is due to the cutting of lines of force and not to the mere presence of the conductor in a magnetic field.

88. ELECTRO-MAGNETIC INDUCTION. (*a*) *Required.*—A strong bar or horseshoe magnet, and a length of wire joined up with a sensitive galvanometer **G**, sufficiently far away as to be out of the direct influence of the magnet.

Experiments. (Fig. 78.)—If the conductor be passed up and down across the field of the magnet near to its pole, momentary currents will be set up, as indicated by the movement of the galvanometer needle. The induced current will be in one direction when the wire is moved down, and in the other when it is moved up: and the directions of both currents will be reversed if the **S** pole of the magnet be used instead of the **N** pole.

Still greater currents will be induced if an inverted horseshoe electro-magnet be used, as depicted in Fig. 79, but in any case a sensitive galvanometer will be required

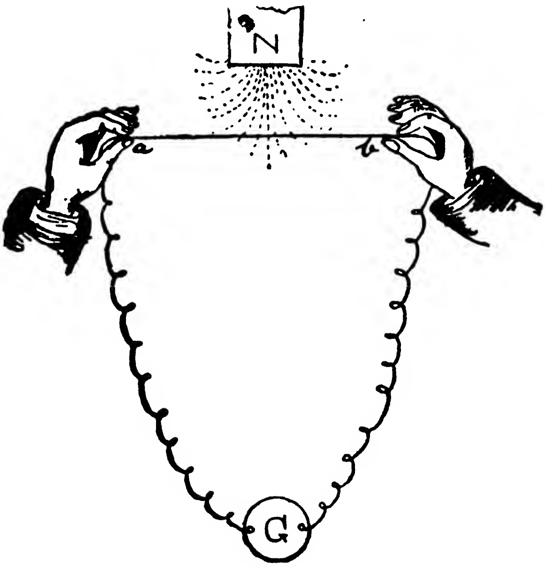
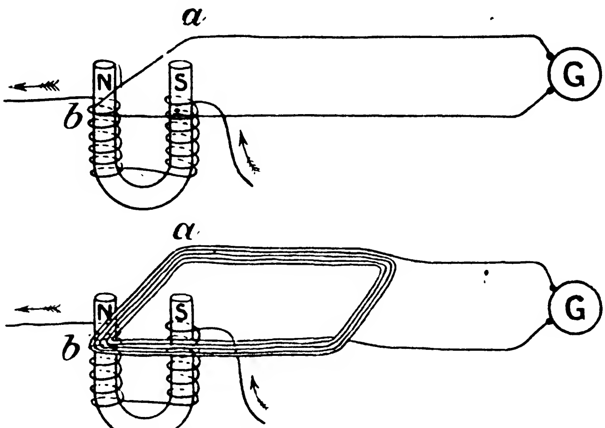


FIG. 78.—INDUCED E.M.F. IN A CONDUCTOR.

if only one length of the conductor be moved across the field.

In Fig. 81, **N**, **S** are the poles of a strong horseshoe magnet placed on end; and *a b* is a wire forming part of a closed circuit in which is a delicate galvanometer **G**. If *a b* be moved downwards across the magnetic field between the poles **N** and **S**, an e.m.f. will be induced, which will give rise to a current in the direction from *a* to *b*. If *a b* be below the field, and be then moved upwards, a current will be set up in the opposite direction, viz., from *b* to *a*.

If a good length of the circuit be coiled up, as shown in Fig. 80, the effect will be very much increased. This is for the reason that the same e.m.f. is induced in each



FIGS. 79 AND 80.—INDUCTION OF CURRENTS.

turn of the coil, the total e.m.f. in the circuit being the sum of these separate e.m.f.'s.

(*b*) *Required.*—A bar magnet, and a coil of many turns

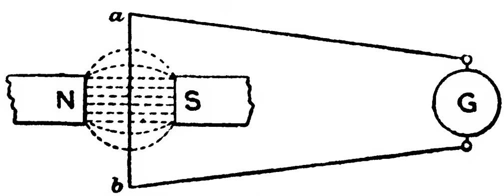


FIG. 81.—ELECTRO-MAGNETIC INDUCTION.

of wire (into which the magnet may be passed) connected to the terminals of a galvanometer **G** (Fig. 82).

Experiment.—If the bar magnet be brought up to the coil an e.m.f. will be induced in the coil, and there will be, while the motion takes place, a momentary induced current in one direction, as shown by the galvanometer.

On taking the magnet away again; there will be a momentary induced current in the opposite direction. The approach of the **N** pole of the magnet induces a current in the opposite direction to the current induced by the

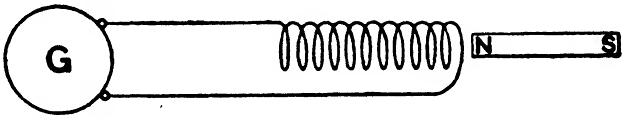


FIG. 82.—INDUCTION OF CURRENTS.

approach of the **S** pole. Again, with either pole, the direction of the induced current depends upon the end of the coil to which it is brought up. If the magnet be pushed right into the coil, a greatly increased effect is obtained.

The coil may be moved instead of the magnet, the latter being stationary. In this case, bringing the coil up to

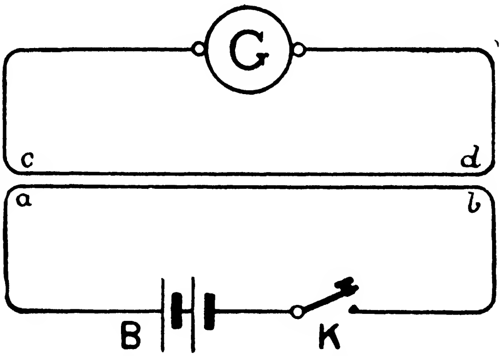


FIG. 83.—INDUCTION OF CURRENTS.

the magnet will have the same effect as bringing the magnet to the coil, and so on.

(*c*) In Fig. 83 two distinct circuits are represented, one containing a battery **B** and a key **K**, and the other a sensitive galvanometer **G**. The portions *a b* and *c d* of the circuits are laid for some 2 or 3 yards very close together and parallel with each other, but *not* in metallic contact.

If the key be depressed, the current in *a b* induces a momentary reverse current in *c d*. And when the current in *a b* is stopped, a momentary direct current will be induced in *c d*. Keeping the circuit closed, the same effect will

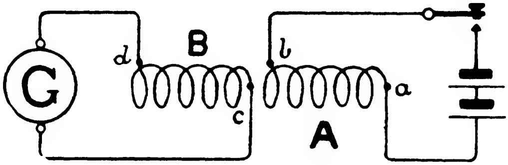


FIG. 84.—INDUCTION OF CURRENTS.

be obtained if the wire *a b* be taken away from or brought up to *c d*; the currents induced being respectively direct and reverse. By the term *direct current*, as here used, is meant an induced current flowing in the same direction

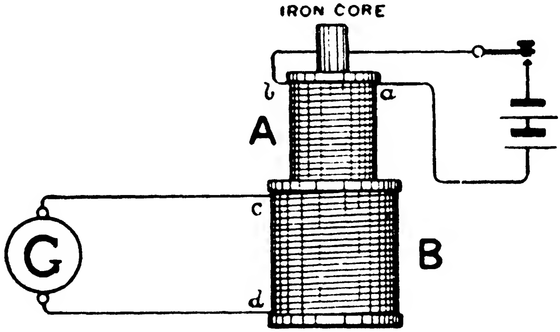


FIG. 85.—INDUCTION OF CURRENTS.

as the inducing current; while a *reverse current* is one flowing in the opposite direction to the inducing current.

(*d*) As—in Exp. (*b*)—a greater effect was obtained by coiling the circuit up; so, in the last experiment, if the portions *a b* and *c d* of the two circuits be coiled up, as shown in Fig. 84, the induced currents will be much stronger. The flow of electricity in coil **A**, or the approach of coil **A** (while carrying a current), will induce a reverse current in **B**. The interruption of the current in coil **A**, or the recession of **A** (while carrying a current) from **B**, will induce a direct current in **B**.

(*e*) The effects obtained in Exp. (*d*) are much increased if the coils be slipped one within the other, as partly shown in Fig. 85, and still more so if they be provided with a soft iron core common to both.

(*f*) While the coils are one within the other, and the key is kept down, no movement of the galvanometer will be detected. If now the iron core be first introduced into and then withdrawn from the coils, momentary reverse and direct currents will be indicated.

Bearing in mind that the strength of the induced current depends upon the number of the inducing lines of force, and the number of turns of wire cut by the lines, the increased effects obtained by: (i) coiling the wire up, (ii) placing one coil within the other, and (iii) introducing the iron core, should be easily understood.

89. LAWS OF ELECTRO-MAGNETIC INDUCTION.

(i) *Let any conducting circuit be placed in a magnetic field; then if by a change in position, or a change in the strength of the field, the number of lines passing through or interlinked with the circuit be altered, an e.m.f. will be induced in the circuit, proportional to the rate at which the number of lines is altered.*

(ii) *A decrease in the number of lines of force which pass through a circuit induces a current round the circuit, in the positive direction (i.e. induces a "direct" current); while an increase in the number of lines of force which pass through the circuit induces a current in the negative direction (i.e. induces a "reverse" current).*

(iii) *The total induced electromotive force acting round a closed circuit is proportional to rate of increase or decrease in the number of lines of force which pass through the circuit.*

The first, or Faraday's, law states that the magnitude of the e.m.f. depends upon the number of lines, and the rate at which they vary. Thus a large number of lines varied slowly would give the same induced e.m.f. as a small number of lines varied rapidly.

The second law gives a sense of direction, telling us that if the cutting of lines of force brings about an increase in those threaded through the circuit, the e.m.f. induced is in the reverse direction to what it is when the cutting causes a decrease. Dropping *a b* down between the poles of the magnet in Fig. 79, causes an increase in the lines threaded through the circuit *a b* G, and raising it up causes a decrease.

There are two ways of looking at the question. One is to think of the cutting of lines—the cutting being most effective when it takes place at right angles, in the same way as a scythe cuts grass, the cutting edge moving at right angles to the blades of grass.

The other way is to think about the number of lines threaded through the circuit and the rate at which that number increases or diminishes. Both of these mean the same thing and lead to the same result. The electric and magnetic circuits are always linked together like two links in a chain. Two links are always at right angles to one another, like a key with a ring. To take the ring off the key, or the key off the ring, the ring must be slightly opened (the air-gap between the poles of the magnet in Fig. 79). Then the ring and key are separated (the lines of force in the air-gap are cut—it follows—the lines of force threaded through the eye of the key are reduced to nothing).

In Fig. 83 the electric circuits *a b* and *c d* are like the first and third links of a chain. They are parallel or in the same plane. When a current is started in *a b*, the lines of force created thereby are at right angles to *a b* and therefore at right angles to *c d*. They start and grow, just as the jets of water in a fountain start and grow when it is set " playing." In so doing the lines of force cut the conductor *c d* as they encircle it. When the current in *a b* has reached a steady value, as it will do in the fraction of a second, then *a b* and *c d* are linked together by these lines of force, which we imagine as concentric circles having their centres on *a b*. By that time the number of lines of force has ceased to alter and, as soon as this is the case, there is no further induced e.m.f. produced in *c d*.

Two electric lines, say telegraph wires, which run parallel to each other for even a short distance may influence one another when in use, just as *a b* and *c d* in Fig. 83. Hence electric light and power cables are never allowed to have a parallel course to the P.O. overhead wires, and where one has to cross the other the regulations require this to be done as nearly at right angles as possible. As two wires crossing at right angles have the plane of lines of force from one parallel to the other wire, there is no cutting of such lines, and consequently no mutually inductive effect.

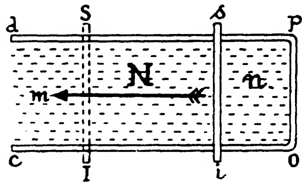


FIG. 86.

A common illustration of the conditions necessary to produce an induced e.m.f. is reproduced in Fig. 86, *c o p d* represent a copper rod forming three sides of a rectangle. The dots indicate the lines of force of a uniform magnetic field at right angles to the plane of the conductor. Another piece of copper rod is placed across and held against *c o* and *d p*. Then the rod forms a *sliding inductor* if it slides along in the direction *m*, from the position *s i* to **S I**. Moreover, *s i* cuts as many lines of force as there are between its first and second positions, and it does so at a rate = **N**/*t*. We may also say that while there were *n* lines threaded through the circuit *s p o i* at first, when the slider has reached the position **S I** the number of lines now threaded through the circuit **S** *p o* **I** will be **N** + *n* or an increase of **N** lines. In this case the important factors are **N** lines, and *t*, the time it has taken the slider to move from the position *s i* to that of **S I**.

Suppose that *d p* and *c o* represent the two rails on the permanent way of a railway and *s i* the axle of one of the carriages. If *o p* be joined together somewhere there is a closed electric circuit, and if *s i* cuts the magnetic field of the earth a current will flow round that circuit taking some power from the locomotive to keep it flowing. In Britain the earth's field, although not quite vertical, is sufficiently so for lines of force to be cut by *s i*. The same thing would happen in Australia but the direction would be reversed. Anywhere near the Equator the earth's field is nearly horizontal, so to whatever point of the compass the train was running this field would not be cut by *s i* moving horizontally. This may be followed by considering the field in Fig. 86 as remaining unaltered, and turning *c o p d* round, up and down the page, when *s i* would still cut **N**, but if the field were turned at right angles till it lay in the plane of the paper no lines would be cut whichever way we shift the rectangle and its slider.

90. LEFT-HAND RULE. When a conductor is moved across a magnetic field, it is more correct to speak of e.m.f., and not current as being induced in the conductor, this e.m.f. giving rise to a current if the conductor form part of a closed circuit. The direction of this induced e.m.f. may be determined by the following rule, if the + direction along the field be known.

Place the left hand across the conductor with the palm facing the conductor, and the thumb, forefinger, and other fingers stretched out at right angles, as shown in the figure; the forefinger must point in the positive direction along the field, and the other fingers in the direction of motion. The thumb will then denote the direction of the induced current.

91. COMMENTS ON EXPERIMENTS. The left-hand rule may be applied to predict the direction of the induced currents in the experiments illustrated. In Fig. 82, think of the tuft of lines proceeding from the **N** pole of the magnet, and the direction in which they cut the first turn of the coil. In Fig. 83, imagine an end view of the wires *a b* and *c d*; figure to yourself the circular lines spreading out from *a b* and collapsing again, when the primary or inducing circuit is respectively made and broken, and think of the direction in which they cut the wire $c\ d$. In Fig. 84 the lines-of-force due to coil **A** are practically the same shape as if **A** were a bar magnet; and having found the polarity of one end of **A** by one of the rules already given,

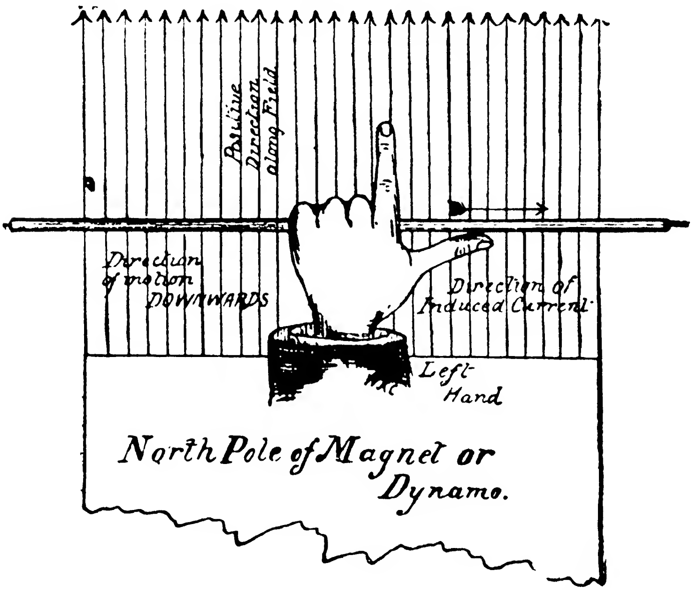


FIG. 87.—LEFT-HAND RULE FOR FINDING THE DIRECTION OF THE E.M.F. INDUCED IN A CONDUCTOR WHICH IS MOVED ACROSS A MAGNETIC FIELD.

A may be looked upon as a bar magnet. Then the direction of the currents induced in **B** may be predicted.

When the coils are one within the other (Fig. 85), one may think of the lines spreading out from and collapsing into coil **A** when the circuit is respectively made and broken, and the direction in which these lines cut the outer coil **B**. In Exp. (*f*), when the iron core is inserted, many additional lines spread out from the inner coil and cut the outer coil. When the core is withdrawn, these extra lines collapse and again cut the outer coil.

92. LENZ'S LAW. *In all cases of electro-magnetic induction, the direction of the induced currents is such as to tend to stop the motion producing them.* We may apply this law to predict the direction of induced currents in certain cases, bearing in mind that to induce or set up a current in an otherwise inert conductor, power has to be expended.

In Exp. (*a*) (Figs. 78–80), the direction of the induced current is such that the conductor *a b* (while carrying the induced current) tends to move across the field* in the reverse direction to that in which it is being moved, and so opposes the movement which causes the e.m.f. to be induced in it; the wire actually requiring more effort to move it up or down across the field than if the field did not exist, though in this case the effort is inappreciable.

In Exp. (*b*) (Fig. 82), the direction of the induced current is such as to create a momentary *N* pole at the end of the coil nearest the magnet, on bringing the **N** pole of the magnet up to the coil (or the coil up to the magnet): and a momentary *S* pole on separating the coil and the magnet. The magnetic effect of the induced current thus opposes the motion of the magnet which produces it. In other words, work is done in bringing up the **N** pole against the repulsion of the induced *N* pole; and in drawing it away against the attraction of the induced *S* pole.

If the circuit of the coil be open the e.m.f. is induced as before but no current can flow, hence no work has to to be done in moving the magnet.

In Exp. (*c*) (Fig. 83), the circuits being stationary, when **K** is depressed the lines of force due to the current in *a b* cut *c d*, and induce a momentary reverse current therein. The lines due to this induced current in *c d* then spread out, cut *a b*, and cause a direct e.m.f. to be set up in *a b*, so that the battery e.m.f. will be momentarily assisted. The *inductance* of *a b* retards the current in *a b*,

* A current-carrying conductor tends to move of its own accord across any magnetic field in which it is placed.

so that it does not rise all at once to its full value : and *mutual induction* between *a b* and *c d* assists the setting up of the current in *a b*. In other words, the effects of inductance in the primary circuit are, as a rule, lessened by the presence of a closed secondary circuit, the momentary expenditure of energy thus saved from overcoming self-induction being absorbed in setting up the induced secondary current.

On breaking the primary circuit at K, a momentary direct current is induced in *c d*, and this current tends to create an opposing e.m.f. in *a b*, which assists in bringing the current in *a b* to zero. Inductance prolongs the current in *a b*, while mutual induction between *a b* and *c d* tends to assist the stoppage of current in *a b* on breaking circuit. In other words, when the primary circuit is alone concerned, the energy of the collapsing field goes to the production of an *extra current*. When a secondary circuit is present, however, most of this energy is expended in setting up a momentary current in that circuit, and the extra-current effect in the primary circuit is lessened.

This is the action of a copper tube when placed over a solenoid, or between the core and the coil of an electromagnet. It reduces the inductance of the magnet, and the extra-current sparking at the contact-breaker in the circuit of the coils and battery. This it does by having induced currents circulated in itself, these induced currents causing a momentary absorption of energy *both* on the make and break of the primary circuit.

It should now be clear how the energy necessary for the setting-up of the induced currents in the secondary circuit is derived from the primary circuit. It should also be remembered that, in the case of a direct current, the effects of self and mutual induction are only momentary, and occur *only* on the making or breaking of the circuit. A very short time after closing a circuit with a constant direct e.m.f. in it, the current in that circuit will depend simply on Ohm's law.

When the circuits (Fig. 83) are moved relatively to each other, the explanation is as follows. When the key is kept down, and *a b* is brought up to *c d*, work is done against the repulsion set up between the primary current in *a b* and the secondary induced current in *c d*. When *a b* is withdrawn, work is done against the attraction between the inducing and induced currents. The work expended in each case represents the energy necessary for the setting up of the currents in *c d*.

In Exp. (*d*) (Fig. 84), we may again look on coil **A** as a bar magnet, having, say, a *S* pole at its left-hand end. Then, according to Lenz's law, the momentary induced current in coil **B** will be such as to create a *S* pole at its end nearest **A** when the current in **A** is started, or when **A** is approached: and a *N* pole at that same end when the current in **A** is stopped, or when the distance between **A** and **B** is increased.

In Exp. (*f*) (Fig. 85), let us think of the adjacent ends or poles of the inner and outer coils, when the former is right inside the latter. Inserting the iron core strengthens both poles of the inner coil; and the momentary current in the outer coil will be such as to give adjacent poles similar to those of the inner coil. Withdrawing the iron core weakens both poles of the inner coil, and the current in the outer coil will then be in such a direction as to give adjacent poles opposite in polarity to those of the inner coil.

93. PRACTICAL APPLICATIONS OF INDUCTION. Referring to Fig. 83, the e.m.f. induced in *c d* will be practically the same as the inducing e.m.f. in *a b*. We may, however, increase the e.m.f. in the secondary circuit *c d* by having a number of turns of wire therein, as in the circuit shown in Fig. 80.

Similarly, in Figs. 84 and 85, the e.m.f. induced in **B** may be made proportionately greater or less by having either more or less turns of wire on **B** than on **A**.

This fact is made use of in various ways. Thus it is the principle of the *alternating-current transformer*, by means of which the e.m.f. or pressure in an alternating-current circuit may be increased or decreased to any required degree. The transformer consists essentially of two separate sets of coils mounted on a laminated-iron frame, the alternating current in the primary circuit setting up an alternating magnetic field (i.e. one changing in direction several times a second) which induces an alternating pressure in the secondary circuit. The prineiples and uses of transformers are dealt with in Chapter XVI.

94. THE INDUCTION COIL embodies another practical use of the induction of currents. Referring to Fig. 85, if the key be tapped down at rapid intervals, an intermittent current will be set up in **A**, and a correspondingly intermittent current induced in **B**. And the greater the number of turns of wire on **B**, the greater will be the e.m.f. of the currents induced therein.

This is the principle of the induction coil, which consists essentially of an iron core wound first with a few turns of thick wire—the *primary coil*—and then with a great many turns of exceedingly fine wire forming the *secondary coil*. The iron core consists of a bundle of annealed-iron wires, in order that it shall be susceptible to rapid magnetization and demagnetization. As the object of an induction coil is to get an induced pressure equal to many thousand volts, it is necessary that the secondary coil should have a far greater number of turns than the primary. But in order that these turns shall not be too far removed from the influence of the inducing magnetic field of the primary, and to economize in space and in copper at the same time, the secondary coil is wound with exceedingly fine silk-covered wire. The wire usually employed is so very fine that—including its covering—it is no thicker than ordinary sewing cotton.

The current in the primary circuit is rendered rapidly intermittent by some form of " make-and-break " device, the simplest of which is similar to that of an electric bell.

Fig. 88 illustrates the principle of the induction coil. Here **IC** is the iron core, P^1 and P^2 the ends of the primary coil, and **ST**, **ST**, those of the secondary coil. **A** is a soft-iron armature attached to a spring fixed at **F**, and carrying a platinum contact-piece **CP** against which bears the platinum point of the contact stud **CS**. Platinum is used at these points as it preserves a good clean contact surface, and is little affected by spark-wear. **BT** and **BT′** are the terminals to which the battery **B** is connected, a reversing switch **R** being interposed. The latter, in its simplest form, consists of two contact arms **A′** and **A″**, each of which is pivoted at one end, and which are connected

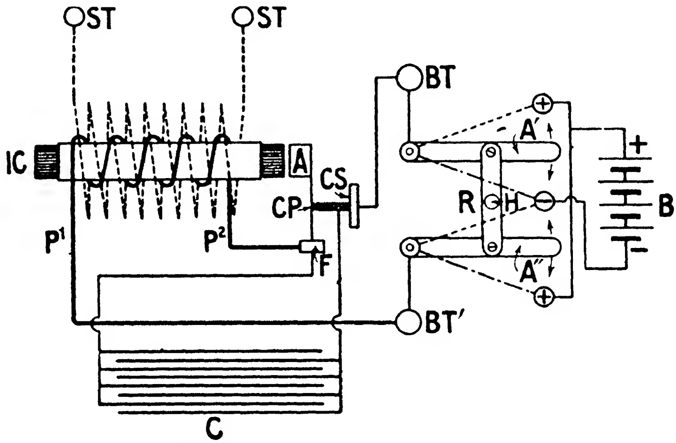


FIG. 88.—DIAGRAM OF INDUCTION COIL.

across by an insulating bar carrying a handle **H**. The battery having its − pole connected to the centre contact stud, and its + pole to two contact studs on either side; by moving **H** one way or the other the direction of the current through the primary coil may be reversed at will. In the figure, the switch **R** is shown in its off position.

The current being switched on, the armature of **A** will be attracted by the iron core, but the moment this occurs the circuit will be broken at **CP**, **IC** will be demagnetized, and **A** will fly back under the influence of the spring. Contact will then be made again, the core once more magnetized, and the circuit broken again. This make-and-break action will take place very rapidly, and the intermittent magnetic field will induce a high intermittent pressure in the secondary coil, which should be great enough to set up a stream of sparks between the slightly-separated extremities of wires attached to **ST**.

The action is greatly improved by connecting a condenser **C** to the contact-stud **CS** and the spring on which **A** is mounted. The condenser helps the battery current to overcome the inductance of the coil more quickly on the make of the circuit, and lessens the sparking at the contacts when the circuit is broken.

As the p.d. between the secondary terminals of an induction coil is so high, it follows that the current will be very small indeed, as the power (in watts) developed in the secondary circuit is always less than that in the primary, a certain amount of power being lost in magnetizing the core, and in overcoming the resistance of the secondary winding.

Induction coils are extensively used for providing the ignition spark for gas and oil engines ; and also in telephony, wireless, vacuum-tube work, etc. The form of the coil varies according to the purpose for which it is intended, but the principle is the same in every case.

95. SELF-INDUCTION may be defined as *the cutting of a conductor by lines of force produced by its own current.* When a current begins to flow along a circuit, it sets up a magnetic field around the conductor. This magnetic field, in being set up, reacts upon or cuts the conductor, and induces a momentary reverse e.m.f. in it. When the current flowing along a conductor is stopped, the magnetic field collapses, and in so doing cuts the conductor. In consequence, another momentary e.m.f. is induced in the conductor which is " direct," i.e. in the same direction as the inducing current.

The effect of inductance, as it is often termed for brevity, is to oppose momentarily the setting up of a current in a circuit, by reason of the opposing " reverse " e.m.f. ; and to retard momentarily its " breaking " or cessation. because of the momentary " direct " e.m.f.

Inductance is not very noticeable in straight conductors, as the conductor cannot be cut by the lines so effectively as when it is coiled up. And as the lines of force set up in a circuit are more crowded if the circuit be coiled up, and are increased in number if the coils have iron cores, inductance is always greatest in circuits containing electro-magnets.

The sparks observed at the contact points in an electric bell, or when a circuit containing a magnet is broken, are principally due to the collapsing of the lines of force of the magnet. These lines cut the coils of wire, and give rise to a momentary *direct* e.m.f. that sets up an *extra current.*

The low pressure from a battery used to operate an electric bell is insufficient to cause any shock to be felt if the two ends of the wire be grasped. If connection be made to the two ends of the magnet coils when the bell is vibrating and the circuit is being broken rapidly, the induced e.m.f. in the coils may give a smart shock. If the solid iron cores of the magnet are replaced by laminated cores the intensity of the shock will be increased as eddy currents cannot then circulate in the cores, the lines of force will change their value quicker, and the induced e.m.f. will be greater.

If an electro-magnet be shunted, or have a resistance placed across its terminals, when the circuit in which it is inserted is opened, there is a path provided in which the induced direct current can circulate. Consequently the action of the magnet is rendered sluggish, as the tendency is to prolong its magnetization.

The effects of inductance are noticeable in a circuit not only when a current is set up or stopped, but also when the current is increased, diminished, or reversed. Such increase, diminution, or reversal, alters the number of lines of force passing through or interlinked with the circuit, and (in the latter case) their direction also, and therefore gives rise to momentary induced e.m.f.'s.

Thus it is that inductance is always present in an alternating-current circuit, and it is mainly because of this that Ohm's simple law does not apply thereto.

96. INDUCTANCE is usually denoted by the letter L. If a coil has N turns, and a direct current C produces a flux or "flow" of magnetic lines through the coil equal to F, then,

$$L = \frac{N\mathsf{F}}{C}, \text{ each quantity being in c.g.s. units.}$$

The derivation of this formula is as follows—

The e.m.f. of inductance = the rate of change of the *flux turns*, i.e. $N\mathsf{F}$.

" " " " also = the rate of change of the product LC.

Hence $LC = N\mathsf{F}$ and $L = \frac{N\mathsf{F}}{C}$

The reason for dividing by C is that the inductance must be expressed in terms of the flux-turns due to unit current.

Thus L is proportional to the number of lines of force cut by the N turns when unit current is suddenly turned on or off; for if $C = 1$ then $L = N\mathsf{F}$. We have to consider the number of lines cut by the whole circuit, i.e. $N\mathsf{F}$. Thus if a coil have 200 turns, and 2,000 lines be set up, the total number of lines cut will be $200 \times 2000 = 400{,}000$.

The practical unit of inductance is the *henry*, and to express L in henries, we must divide the number of lines cut ($N\mathsf{F}$) by 1000 million. The cutting of one line (per sec.) represents the setting-up of 1 c.g.s. unit of e.m.f., and as the volt is 100 million times the c.g.s. unit, 100 million lines must be cut (per sec.) to generate 1 volt.

Thus—

$$L \text{ (henries)} = \frac{N\mathsf{F}}{C \text{ (in amperes)} \times 100 \text{ million}}$$

Since 1 c.g.s. unit of current is equal to 10 amperes.

A *henry* may therefore be defined as the inductance in a direct-current circuit such that the sudden starting or stopping of 1 ampere of current causes 100 million lines to be cut by the circuit.

In a solenoid without an iron core, L varies with the square of the number of turns in the coil, since each turn not only adds to the value of F, but also to N.

When a direct current is switched on through the coils of a magnet, the pull of the magnet gradually increases as the back e.m.f. of inductance dies away: when the current is steady, the pull is steady.

97. NON-INDUCTIVE WINDINGS. It is important that resistance coils for measurements should have no self-inductance. By doubling the wire of which they are wound upon itself, as in Fig. 89, each half of the coil neutralizes the other's magnetic effect, and the coil has, consequently, no inductance. Such coils are said to be wound *non-inductively*.*

Resistances used to carry fairly heavy currents and dissipate energy generally have no insulating covering. Sometimes it is necessary to have the resistance entirely non-inductive. The energy-dissipating coils may then be wound non-inductively by Mather and Duddell's method. In this case, each coil consists of two helices having the same number of turns and the same resistance, but wound in opposite directions, the one left-handedly and the other right-handedly. The two helices are fitted into each other and connected together at both ends, as illustrated in Fig. 90. The current then flows through them in parallel, and the magnetic effects of the two portions neutralize each other, the combination acting as a non-inductive coil.

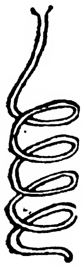


FIG. 89.

Yet another method of obtaining a resistance, with a very low inductance, is to wind the wire on thin strips of

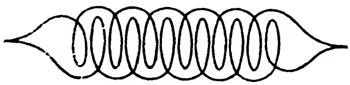


FIG. 90.—PARALLEL NON-INDUCTIVE HELICES.

insulating material, as shown in Fig. 91, where I is the insulating strip. The illustration gives a side and an end view of this arrangement, and it will be seen that the two sides of the coil are so close together that they practically neutralize each other's magnetic effect.

98. MUTUAL INDUCTANCE takes place when neighbouring current-carrying circuits act inductively upon

* The different ways of winding coils to have negligible inductance are explained in Chapter III of B. Hague's *Alternating Current Bridge Methods*. (Pitman, 25s.)

one another, and may be defined as *the cutting of a circuit by lines of force produced by a current flowing in another circuit.*

Currents in neighbouring portions of the same or different circuits will attract each other if they flow in the *same*

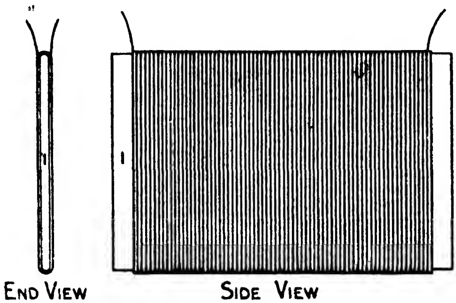


FIG. 91.—NON-INDUCTIVE RESISTANCE.

direction, and will repel each other if they flow in *opposite* directions. Thus, in Fig. 92, the two portions **A B** and **C D** will attract each other, while in Fig. 94 they will

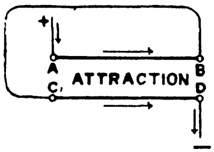


FIG. 92.

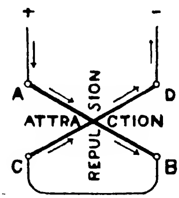


FIG. 93.

ATTRACTION AND REPULSION OF CURRENTS.

repel each other. If the wires cross each other, the attraction and repulsion between the various parts will tend to make them close-up eventually like a pair of scissors. Thus, in Fig. 93, the wires **A B** and **C D** will tend to shut up so that the ends approach each other; while in Fig. 95, **A D** and **C B** will approach. Referring to Fig. 93, consider each wire as divided into halves at the point where they cross, and call this point X. Then, when we consider the statement made at the beginning of this paragraph and the directions of the currents, it must be clear that attraction is set up between **A** X and **C** X, and also between **B** X and **D** X; while repulsion takes

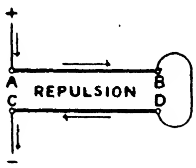


FIG. 94.

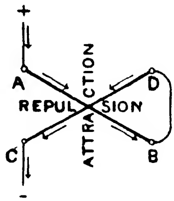
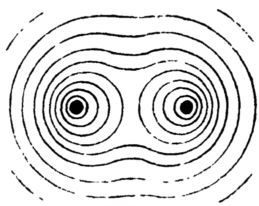


FIG. 95.

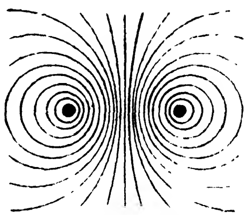
ATTRACTION AND REPULSION OF CURRENTS.

place between **A** X and **D** X, and between **B** X and **C** X. The same argument, with the letters altered, is applicable to Fig. 95.



ATTRACTION

FIG. 96.—ATTRACTION OF CURRENTS.



REPULSION

FIG. 97.—REPULSION OF CURRENTS.

The reason for the actions just explained will be understood from the above magnetic figures given by two neighbouring vertical current-carrying conductors; the currents being in the same direction (either up or down) in the first case, and in opposite directions in the second case.

It is a property of lines of magnetic force running approximately in the same direction to tend to lie as far as possible side by side, and so follow the same circuit. Hence the merging of the two fields in Fig. 96. The lines-of-force then tend to shorten themselves. and in so doing draw the conductors together. In Fig. 97, the currents and the fields due to them are in opposite directions; the two fields are consequently distorted, and in endeavouring to place themselves symmetrically with regard to their respective conductors, force the latter apart.

When adjacent fields run in opposite directions, the lines of each will alter their shape so as to run as far as possible side by side, and in the same direction. When adjacent fields run in the same direction, the lines will mutually repel one another. It follows that there is repulsion between the lines of any given field, tending to force the lines apart.

99. MAGNETIC DRAG. The property of attraction and repulsion of currents, due to the interaction of their fields, is similar to that governing the motion of a current-carrying conductor when placed in the field of a magnet.

When a conductor carrying a direct current is placed in a magnetic field, at right angles with the lines of the latter, it will experience a force dragging (or tending to drag) it across the field, in a direction depending upon the relative directions of the current and of the field. This force is due to the interaction between the field set up by the current in the conductor and the field in which it is placed; and is proportional to the product of the strength of the two fields.

If a copper needle be suspended by a fine wire through its eye, and its lower end dip into a circular trough of mercury, through the centre of which a bar-magnet projects vertically, and if a current flows into the mercury and up the needle and its suspending wire, the lower end of the needle will swing or revolve round the magnet.

The reason for the action described may be explained as follows: *c* in Fig. 98 (*a*) represents a conductor passing perpendicularly through the paper. A current flowing in this conductor towards the reader produces a circular magnetic field around the conductor, the direction being counter-clockwise, as indicated by the arrow-heads.

In (*b*) **N** and **S** are two magnet poles ; the field between them, except at the edges, consisting of straight lines, whose positive direction is from **N** to **S**.

Now suppose *c* to be placed in the field between **N** and **S**, as shown in (*c*). On the lower side of *c* the lines of force due to *c* and those due to **N S** will be opposing one another, whilst on the upper side they will be acting in the same direction. The resultant magnetic field will consequently

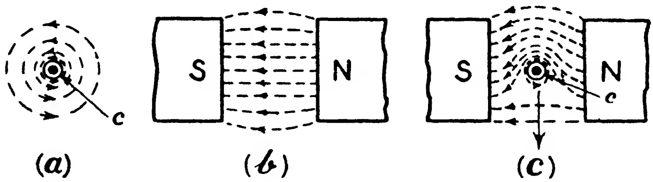


Fig. 98.

be somewhat as indicated by the dotted lines in (*c*) ; the current-carrying conductor *c* distorting the previously uniform magnetic field of (*b*), causing the lines of force to be bent and crowded on one side of the conductor.

When lines of force are passing in the same direction they tend to repel, whereas those in opposite directions tend to attract one another ; consequently the conductor in (*c*) experiences a force tending to move it in the direction of the large arrow. This arrow, therefore, indicates the direction of the magnetic drag, which is at right angles to the permanent field. If the current in (*c*) were downwards through the paper instead of upwards, the direction of the magnetic drag would be reversed.

The reader should draw figures to prove for himself that the conductor would still tend to travel in the *same* direction if the direction of the current and the polarity of the field-magnet were *both* reversed ; and that it would tend to travel in the *opposite* direction if the current *alone* or the magnet's field *alone* were reversed.

The force on a current-carrying conductor in a field may be explained in another way, by saying that the drag is due to the effort of the field to regain its normal shape, the stretched lines tending to shorten themselves. This idea enables us to employ a mechanical analogy (Fig. 99) to illustrate magnetic drag. Here the distorted field is represented by the stretched elastic band E E, which, in its endeavour to assume its usual position, forces the rod R (which represents the conductor) in the direction indicated by the arrow. If we imagine a row of elastic bands

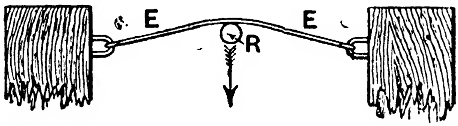


Fig. 99.—Analogy illustrating Magnetic Drag.

behind E E, all pressing on R, it will be understood that the greater the length of current-carrying conductor in the field, the greater will be the drag or force.

On this phenomenon of magnetic drag depends the action of all electric motors; for the armature being situated in a magnetic field, and having current *sent through*, or (as in the case of most alternating-current motors) *induced in* its conductors, is set in motion thereby. Direct current motors are dealt with in Chapter XI, and alternating motors in Chapter XVII.

100. THE DIRECTION OF MOTION OF A CURRENT-CARRYING CONDUCTOR IN A MAGNETIC FIELD. As the direction of the magnetic drag on a current-carrying conductor depends both upon the direction of the current, and of the field in which the conductor is placed, an easily-remembered rule is handy. Such a rule is as follows: *Place the right hand with the palm facing the conductor, and the thumb, forefinger, and the other fingers (grouped together) stretched out at right angles with one another. The forefinger must point in the positive direction along the field and the thumb in the direction of the current; then the other fingers* *will denote the direction in which the current-carrying conductor will move.*

101. MAGNETIC BRAKES. Magnetic drag always exists between a current-carrying conductor and the magnetic field in which it happens to be placed. The

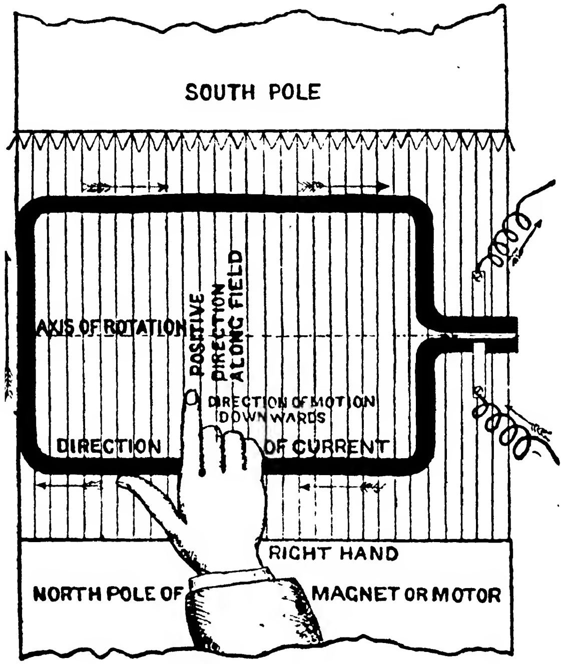


FIG. 100.—MOTION OF A CURRENT-CARRYING CONDUCTOR WHEN PLACED IN A MAGNETIC FIELD.

conductor need not be a wire, it may be a plate or sheet or a mass of metal. The same piece of metal may have a current induced in it by its motion in a field, that is to say, act as an inductor, and then behave as a current-carrying conductor so that the drag retards its motion. There are many practical applications of this principle, and of its opposite, namely, how to prevent a current being induced in a mass of metal which has to be moved across a magnetic field.

If a piece of copper sheet were thrust into the strong field between the poles of a powerful electro-magnet the induced current would be large, as the resistance of the electric circuit is extremely small. The drag, or resistance, to motion would be very great, since both the field is strong and the current large. A copper hatchet used to strike at the air in the gap between the poles of such a magnet would be arrested, as if it had hit something not quite solid but of a very viscous nature, like tar or thick treacle.

The drag can be avoided by opening the electric circuit, as could be done by cutting slots across the plate with the slots so arranged as to intercept or come at right angles to the direction of flow of induced current.

When it is desired to open a circuit quickly, the break, between the lever and fixed contact of the switch for the purpose, is arranged to take place in a magnetic field and the magnetic drag on the current, as the lever and contact are separated, causes the arc to be elongated and driven away. This device is termed a *magnetic blow-out* and is one example of many of the kind.

QUESTIONS

1. Whenever a current flows through a conductor, a magnetic field is set up round the conductor. Conversely, when an independent magnetic field is brought up to a conductor or a conductor is moved across a magnetic field, a momentary e.m.f. is set up in that conductor. Explain these effects.

2. What is meant by an induced e.m.f., and what are the conditions necessary in order that the largest e.m.f. may be induced in any given case ?

3. If the north-seeking end of a magnet be thrust into a coil of wire the ends of which are joined together, what will be the result ? Illustrate by means of a sketch.

4 Suppose a coil of a few turns of insulated wire lapped all round with tape so as to form a firm ring, as in Fig. 100A, be pushed in and pulled out of the field in the narrow space between the poles of a large electro-magnet, explain what difference would be found with the ends of the coil disconnected, and with the ends connected together.

5. Explain exactly why it is that when two single-wire telephone

circuits run parallel to each other for even a short distance, there is over-hearing between the two, but when they cross each other at right angles there is no over-hearing.

6. What do Faraday's laws of electro-magnetic induction tell us as to when an induced e.m.f. is produced, its direction and to what its amount is proportional ?

7. What rule or rules can be given for finding the direction of the induced current when a conductor is moved across a magnetic field ?

8. Show that the current induced in a straight conductor when moved down in front of a North pole of a horizontal bar magnet

FIG. 100A.—TRANSFORMER COIL.
(*Brush Co.*)

is in the same direction as the current induced when the conductor is moved up in front of the South pole of the same magnet.

9. Is a railway train retarded in its motion in any degree by the manner in which any part or parts of it cut the earth's magnetic field ? If so, is the extent of retardation greater or less if the train is running in a northern or southern latitude than if it is running near the equator ? Why is it greater or less ?

10. Suppose a large electro-magnet is provided, having a narrow space between its poles so that a magnetic field of great density and considerable area exists between the pole faces. State, and explain shortly, what you would find if you were to take a plain disc of high conductivity copper, and push it, or allow it to fall, through the space between the poles. What would you find if you took a second disc, similar to the first, but having a considerable number of radial slits cut in it reaching nearly to the centre ?

11. What do we learn from Lenz's law, and how could it be used to predict the direction of currents which we would expect

to find induced when a conductor, forming part of a closed electric circuit, cuts a magnetic field ?

12. How does slipping a copper tube over the core lessen the spark of an induction coil ? When a metal tube is used in this manner, its temperature rises. Why is this ?

13. Give a diagram of the core, windings, and connections of an induction coil, and explain the uses of the various parts. Why is it necessary to use an iron core of fine wires rather than a solid bar of iron ?

14. Describe the contact breaker and how you would construct a condenser, such as required for a small induction coil, and how you would attach them to the coil.

15. The induction coils, used in telephonic apparatus have the primary wound to a low, and the secondary to a high, resistance. Why is this the case ?

16. What is meant by self-induction ? Describe any experiment showing the phenomenon.

17. Give the reason why the inductance in any fixed length of wire is greater when the wire is coiled up as compared with when it is straight, and describe a manner of coiling it up so that it shall have no inductance.

18. Distinguish between self-induction and mutual induction. Why is the self-induction of a coil of wire increased by inserting an iron core in it ?

19. The two ends of the wires from a battery of 4 Leclanché cells can be grasped without feeling any shock, but if an electric bell be placed in the circuit a smart shock may be experienced if connection be made to the right points. Indicate these points and explain what happens. Would any difference be found in the intensity of the shock if the solid iron core of the bell-magnet were replaced by a core made up of a bundle of soft iron wires ?

20. Explain the causes to which the spark, seen on breaking any circuit in which there is an electro-magnet, is due. Why do not the same causes produce a spark when the circuit is made ?

21. Give the principal reasons why there is sparking at switch contacts. What is the reason why switches are usually made with mechanical contrivances so as to snap off quickly when opening a circuit ? Do these reasons indicate that switches ought also to be designed to snap on quickly when closing a circuit ?

22. If a shunt be placed across the terminals of an electro-magnet, used in a relay or automatic switch, the action of the armature becomes sluggish. Explain exactly why this is the case.

23. Why is it that when the current which excites an electro-magnet is cut off, the magnetism takes a longer time to disappear when the electro-magnet is shunted than when it is unshunted ?

24. What is meant by the "self-induction" in an electro-magnet bobbin, and how can it be measured ?

25. Describe the construction of a standard of self-induction and state how you would ascertain the self-induction of any coil in terms of this standard.

26. Describe, with sketch, an arrangement for showing the rotation, around the pole of a magnet, of a conductor carrying a direct current.

27. Explain clearly in what way two neighbouring current-carrying wires tend to act upon one another, and why there is in some cases attraction, and in others repulsion, between them.

28. Sketch the form and distribution of the lines of magnetic force in the field surrounding a long straight conductor which carries a current. Give a second sketch showing similarly the lines of force in the field of two parallel straight conductors carrying current flowing in the same direction.

29. Imagine you have a large powerful electro-magnet with only a short gap between its poles, also that it is excited to produce a strong field in the gap. What effect would be produced on a conductor passing freely through the gap when a current of 100 amps. was caused to flow along the conductor ?

30. Give a theory for the "magnetic drag" subsisting between two neighbouring current-carrying conductors.

31. Give a design for, and show how to construct, some apparatus which will exhibit the attraction and repulsion between conductors conveying electric currents. Who first investigated these electro-dynamic actions ?

32. The leads to a motor taking a large current run up a wall and have fuses inserted in each lead. The fuses are in cast-iron boxes and are mounted on a metal frame. One day the motor fails and a very heavy current melts the fuses, volatilizing the metal of which they are composed. It is found that the top left hand of the left fuse box and the top right hand of the right fuse box are badly burned away. Explain why this action took place.

CHAPTER V

THE ELECTRIC CIRCUIT

102. THE CONDUCTING PATH through which electricity flows may be conveniently divided into four parts: (*a*) the source of electrical pressure—battery, dynamo or alternator; (*b*) the insulated wires or cables, forming the conducting link between the various things in the circuit called the "leads," and on a large scale termed the "mains"; (*c*) the appliances to be worked by the current, or *consuming devices* through which the electricity flows, such as lamps, motors, heaters and signalling devices; and (*d*) the controlling and regulating devices, of the nature of switches, fuses, instruments and rheostats.

An electric bell is the simplest electro-magnetic mechanism. The general principles which underlie the construction of relays and automatic circuit-breakers may be conveniently approached by commencing with electric bell circuits, and the primary batteries commonly used.*

103. THE LECLANCHÉ CELL is extensively used in electric bell and kindred work, where small currents are required intermittently. In its ordinary form it consists of an outer glass vessel containing a solution of sal ammoniac (ammonium chloride), and a zinc rod. In the centre of the outer vessel stands a porous pot of unglazed porcelain, containing a carbon plate tightly packed round with small lumps of crushed carbon and black oxide of manganese (manganese dioxide) in equal proportions. The black oxide acts as a depolarizer.

The carbon plate sometimes has a lead cap cast on to it, in which is imbedded a piece of screwed brass wire carrying a brass nut; this forming the positive pole of the cell. In the best cells, the cap on the carbon is made

* The elementary theory of primary cells is dealt with in the author's *First Book of Electricity and Magnetism.*

of carbon also, and the injurious formation of white lead which takes place with lead-capped carbons is thereby stopped. The zinc rod has a piece of covered copper wire soldered to its top end, the naked end forming the negative pole. To prevent the breaking off of the copper wire, some such device as that illustrated in Fig. 102 is often employed. When a low internal resistance is desired, the zinc rod is replaced by a cylinder of zinc.

The porous pot is sometimes replaced by one made of

FIG. 101.—LECLANCHÉ CELL.

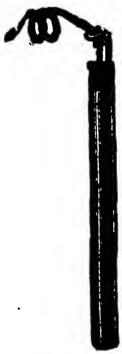


FIG. 102.—ZINC ROD.

sacking, which offers less resistance. In the *agglomerate-Leclanché cell* the carbon and manganese mixture is crushed fine, and formed under great pressure into blocks, which are afterwards held against the sides of the carbon plate by india-rubber bands. These bands also carry rings in which the zinc rod is held, for it is necessary that the latter should not touch either the carbon plate or the agglomerate blocks. In other forms the zinc rod is hung in the centre of a cylinder of compressed mixture.

104. DRY CELLS. *Wet cells* suffer from the disadvantage that they contain liquid, which is liable to be spilt, or to evaporate. So-called dry cells are frequently used in place of them, though such are not really "dry," inasmuch as the electrolyte has the consistency of a jelly.

Though dry cells are known under many different names, they are all practically the same. In a containing vessel, generally of cardboard, is placed a zinc cylinder with wire attached, and in the middle of this stands a carbon plate or rod, the space between being filled with a jelly-like composition. Sometimes the zinc itself forms the outer cell. In some forms, the carbon plate is embedded in a black paste consisting of manganese dioxide and powdered carbon, moistened with a solution of ammonium chloride and zinc chloride. The rest of the space is filled with a white paste of flour and plaster of Paris moistened with the same solution as the black paste. The cell is finally sealed up with melted pitch, vent holes being provided by inserting two pieces of thick wire, and removing them when the pitch has set.

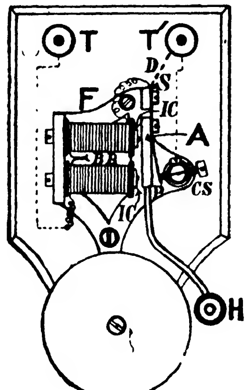


Fig. 103.—Trembling Bell.

There are many different makes of dry cell. Most of them are really modifications of the Leclanché cell, with the addition of zinc chloride. Plaster of Paris and flour or similar materials serve to keep the black or depolarizing paste away from the zinc, but do not play any part in the chemical action of the cell.

105. ELECTRIC BELLS. Fig. 103 illustrates the ordinary *electric bell*, which gives a rapid succession of sounds as long as its battery circuit is kept closed: **F** is the cast-iron frame. *IC*, *IC* are two soft-iron cores screwed into this frame, and carrying bobbins of wire *BB*. **A** is the soft-iron armature supporting the stem and hammer **H**. **A** is held to **F** by the steel spring *S*, the lower extremity of which should be tipped with platinum *P*. *CS* is a contact screw and stud fixed to, but insulated from, the foot of the iron frame. *CS* is connected with the terminal T′. When the magnet cores *IC* are not magnetized by the passage of the current through the coils, the tip of the spring *P* bears against the end of the contact screw *CS*, which should also be tipped with platinum. When the bell is working, each time the spring is drawn away from *CS*, a small inductance spark occurs, which tends to oxidize the contact points. Platinum being an inoxidizable and infusible metal, always presents a clean surface of contact. As platinum is costly, silver is often employed in cheap bells.

The current entering, say, at the terminal T, traverses the magnet coils, and passes to the framework at *S*: from there it goes down the spring to *P* and *CS*, and so to the terminal T′. The iron cores *IC* become magnetized, attract A, and H strikes the gong. In consequence of the attraction of A the circuit is broken at *P*, the current is stopped, the magnet demagnetized, and the force of the spring *S* brings its tip once more against *CS*, when the circuit is again completed, the armature attracted, and the bell struck. Thus the bell-hammer H vibrates rapidly to and fro as long as current is passed through the bell.

If the terminal T′ be connected with the framework, as indicated by the dotted line *D*, instead of with the contact stud *CS*, the bell will act as a *single-stroke bell*. In this case one tap only of the hammer will be given every time the circuit is completed.

The ends of the poles of an electric bell should carry brass pins projecting just far enough to prevent the iron of the poles and armature from coming into contact. If this is not done, *magnetic sticking* will result.

106. BELLS IN SERIES. Two or more ordinary bells cannot be connected in series, but this is possible with the special modification illustrated in Fig. 104. The circuit through the bell is never broken, the attraction of the armature short-circuiting and therefore demagnetizing the electro-magnet, which thereupon releases the armature. This operation is repeated as long as the outer circuit is closed, and the bell rings without interfering with the others in the circuit.

Another form has differentially-wound coils. In Fig. 105, the magnet has two windings of the same gauge of wire which are connected up in opposite senses. Both windings start from the point **P**; one being connected to the other side of the battery circuit as at **A**, while the other is connected at the point **B** to the spring and armature. When

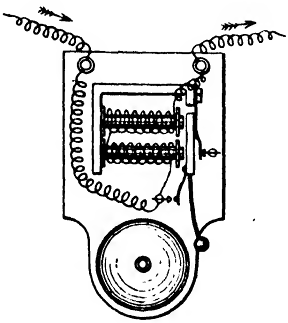


FIG. 104.—BELL FOR SERIES WORKING.

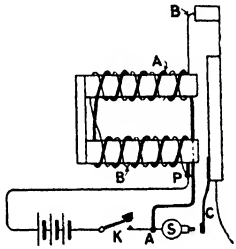


FIG. 105.—DIFFERENTIALLY-WOUND BELL MAGNET.

the circuit is completed, the current first flows round the **A** circuit, by the thick-line winding. The armature is attracted, and contact is made between **S** and **C**; the current then flowing also round the **B** circuit, indicated by the thin-line winding. This demagnetizes the magnet, and the armature consequently springs back. As soon as contact is broken at **S** and **C**, the armature is attracted once more. The vibration of the armature is consequently kept up as long as the battery circuit is closed.

107. PUSHES. The common form of contact maker is the push, and this is too well known to need much description. Fig. 106 shows a push with a view of the springs inside, the latter being shown separately in Fig. 107. The parts where these springs come into contact should be tipped with platinum as shown, for reasons already given. In fact, all *dotting* or "*end*" *contacts* require to be platinum-tipped.

Rubbing or *sliding contacts* are distinguished by the two contact surfaces rubbing over one another and so keeping clean and bright, as in switches.

It is sometimes necessary for the push to have two contacts, above and below the moving spring respectively.

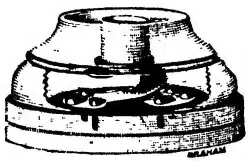


FIG. 106.—PUSH.

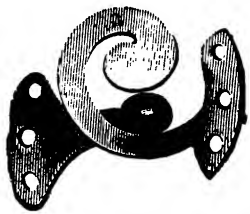


FIG. 107.—PUSH SPRINGS.

Thus three wires are connected to the push. Calling these wires *a*, *b* and *c* and supposing that *a* is connected with the movable spring, *b* with the top contact, and *c* with the bottom contact; in the ordinary position of the push *a*

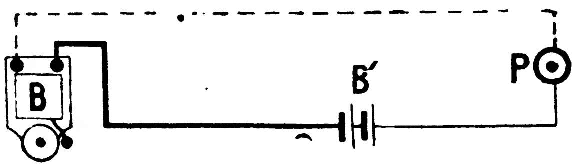


FIG. 108.

is connected with *b*, but when the push-knob is depressed, *a* is disconnected from *b* and connected with *c*. Such a push is called a *two-way* or *double-contact* push.

108. BELL CIRCUITS. Fig. 108 shows a circuit comprising a two-cell battery **B′**, a bell **B**, and a push or other contact **P**. Positive battery wire is shown by a thin line, negative battery wire by a thick line and the wire not directly connected to the battery by a dotted line.

A single cell is represented by a vertical short thick line indicating the zinc or negative pole, and a long thin one the carbon or positive pole.

Fig. 109 illustrates a three-number indicator working from three pushes, and connected with a bell, and a battery. The internal connections of the indicator will be clearly

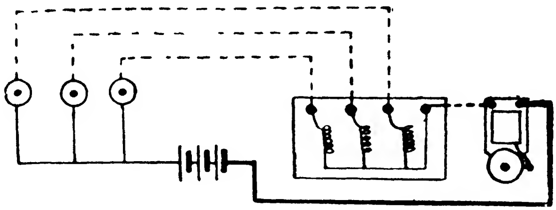


Fig. 109.

seen, the helical lines representing the magnet coils of the indicator movements.

Supposing it is required to connect two places A and B, so that A may ring B's bell, and vice versa, there being a battery at each place. If two-way or double-contact pushes be used, the connection may be made as

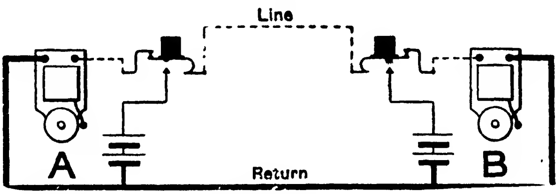


Fig. 110.

shown in Fig. 110, with two wires only; or with one wire and "earth return," i.e. with the return wires soldered to the water pipes, so as to lead the current back through the earth. To do the same thing with ordinary pushes would require three wires between the two places. "Earth return" is only used in cases where the distance is so great that the saving of wire is a consideration.

Two points may be connected so that either can ring the other's bell, with a *battery at one station only* with ordinary pushes, as shown in Fig. 111.

When two or more ordinary electric bells are required to be rung at the same time, from one battery and push for instance, the bells must be connected-up in parallel,

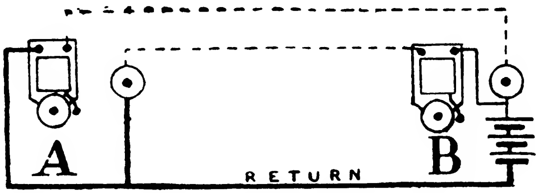


FIG. 111.

so that the current divides between them. Thus Fig. 112 shows three bells joined-up to ring from one push P. When we consider the action of a trembling bell, and think of two such joined-up in series, it will be evident that, unless they made and broke circuit at exactly the same rate (a practically impossible condition), they would either work very jerkily and weakly, or not at all.

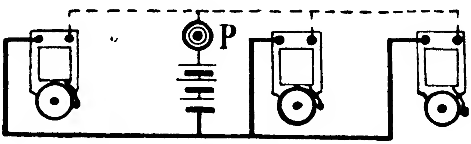


FIG. 112.

109. RELAYS. A *relay* may be defined as an electrically-operated push or switch. When a current flows round the coils of a relay, and its armature is attracted, two contact surfaces are brought together which close another circuit.

A simple form of relay, adapted for bell work, is illustrated in Fig. 113. The coils, armature, back-stop, and contact stud are mounted on an iron frame. The armature is delicately-mounted, its spring being very thin and sometimes perforated to reduce its stiffness still further. A fine helical spring **S** and thumb-nuts enable the tension on the armature to be adjusted to a nicety. The stud and screw **SS** serve merely as a back-stop, while **CS** is a contact stud insulated from the base. The ends of the coils are connected with the terminals **TT**; while the top left-hand terminal **T′** is joined-up to the frame work, and is thus in connection with the armature contact-spring. The

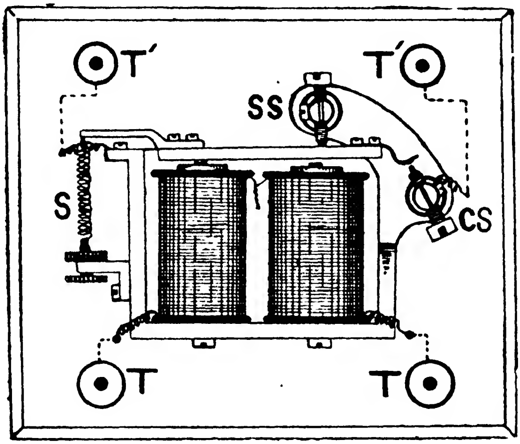


FIG. 113.

contact stud **CS** is connected to the top right-hand terminal **T′**. The armature being very lightly adjusted, a weak current flowing in and out by the terminals **T T** is sufficient to attract it, and the circuit connected with **T′ T′** is thus completed.

The uses of relays are many. In electric bell work, relays are generally used with indicators,* where the current has to go from the battery to the distant push, thence through the indicator coil and bell, and so back

* Indicators and alarms, and their circuits, are dealt with in the author's *Electric Wiring, Fittings, Switches, and Lamps*, Chapter V. (Pitman, 10s. 6d.)

to the battery. The resistance of the indicator and bell coils, added to the length of wire leading to and from the push, necessitates the employment of a large number of cells to get a sufficiently strong current to ring the bell. This causes excessive sparking at the bell contacts. Relays avoid all this.

Fig. 114 illustrates a simple relay circuit. *P* is the distant push, *I* the indicator-movement coil, *R* the relay, *C* the relay contact, *B* the bell, and *B′* the battery. When *P* is pressed, a steady current flows from the battery

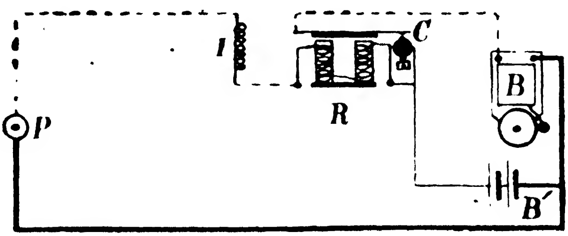


Fig. 114.

through *R* and *I*, and so back to the battery. The indicator is actuated, and the relay contacts are brought together, thus permitting a *separate* strong steady current to flow from the *same* battery direct through the bell. Immediately the push is released, the relay contact is broken and the bell stops ringing. Sometimes two separate batteries are used, one in the relay circuit, and the other in the bell circuit.

A relay for operating trip circuits in power station practice has already been illustrated in Fig. 70.

110. MAGNETO BELL. A magneto bell is one which is worked by an alternating current derived from a *magneto generator*, sometimes called the *ringer*. A magneto machine is, in fact, a small alternator having permanent field magnets, and a shuttle armature. Its action depends upon the fact that if a coil of fine wire wound on an iron bobbin be quickly rotated in a strong magnetic field, a rapidly-alternating current will be generated therein; and this current may be led to the outer circuit by making suitable connections with the rotating coil.

A view of a magneto machine is given in Fig. 115. In this case, three permanent magnets have their like poles united by soft iron pole-pieces, between which the armature is pivoted. A handle outside the case is fitted to a spindle carrying a large toothed wheel, which gears into a pinion

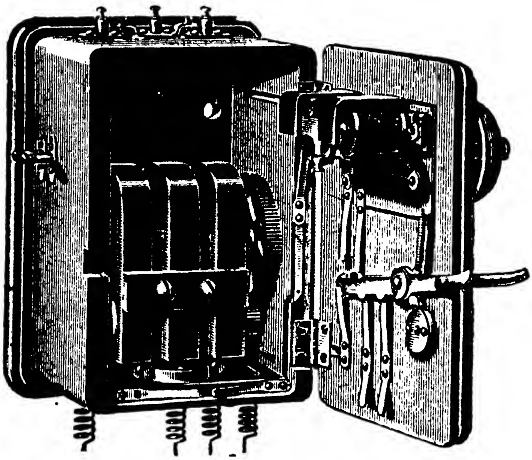


FIG. 115.—MAGNETO GENERATOR.

on the armature spindle. Thus the latter is rapidly rotated when the handle is turned at a moderate speed.

Fig. 116 is a diagram of a magneto bell. There are two coils and cores *c*, *c′* mounted on a yokepiece *Y*, the whole forming a horseshoe magnet. Below is pivoted a light armature *A*, carrying a stem and hammer *H*, which strikes the bells on either side when it moves to and fro. A light spring, riveted at its middle to the centre of the armature, bears on the two poles, and tends to keep the armature horizontal. This is shown at *Sp* in the figure, but it is not essential. Arranged so that its poles come opposite the middles of the yokepiece and armature respectively, is a permanent horseshoe magnet *NS*. The effect of this is to magnetize the magnet cores and armature by induction. Thus the N pole of the magnet induces south polarity at the middle part *s″* of the yoke, and north polarity at the poles of the electro-magnet, as at *n*, *n′*. The S pole of the permanent magnet induces north polarity at the middle of the armature, and south polarity at its two ends *s*, *s′*. Both the magnet cores and the armature are thus polarized, and the direction of movement of the latter depends on the direction of the current round the electro-magnet. Suppose a current flows through the latter

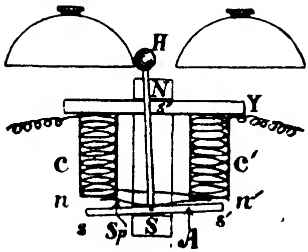


FIG. 116.—DIAGRAM OF MAGNETO BELL.

in such a direction as to make the pole of *c* north and that of *c′* south ; then the induced N polarity *n* is strengthened, while that at *n′* is destroyed, the pole for the time being S. The right-hand pole of the armature will thus be repelled, while the left-hand pole will be attracted, and the hammer *H* will move to the right. If now the current in the coils be reversed, so that *c* is S and *c′* N, the armature will move over the other way. Thus the hammer will vibrate once to and fro with every complete alternation of the current. It will thus be evident that the polarization of the armature enables it to change its movement with changes in the direction of the current ; while the polarization of the magnet cores, which can be readily overcome by the current in the coils, renders the magnet more susceptible to the rapid changes in the direction of the current. Obviously, a magneto bell will not continue to ring if a direct current, as from a battery, be passed through it.

Fig. 117 shows a magneto generator connected-up with a magneto bell. Two or more generators or bells may be put in the same circuit, in series ; and in such a case, when either of the generators is worked, all the bells will ring.

111. THE TELEPHONE is an instrument by means of which sounds may be transmitted electrically from one

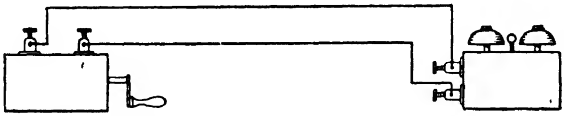


FIG. 117.—MAGNETO-BELL CIRCUIT.

place to another. It consists essentially of two parts, viz., the *transmitter*, into which the words are spoken, and the *receiver*, which reproduces the sound at the other end of the wire.

Bearing in mind that sound consists of vibrations set up in the air by the voice or whatever else emits them, the telephone transmitter may be defined as an instrument

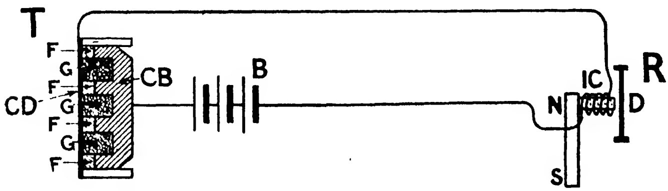


FIG. 118.—SIMPLE TELEPHONE CIRCUIT.

which sets up variations in the current in the circuit corresponding in intensity with the variations of the sound waves. This varying current passes through the receiver, and causes its diaphragm to move in exact correspondence with the movements of the plate of the transmitter, so that fresh sound waves are set up in the air.

In Fig. 118, **B** is a battery, **T** a transmitter, and **R** a receiver.

The transmitter consists primarily of a carbon diaphragm **CD** and a carbon block **CB** ; the two being held together in a case, but out of contact with each other, with felt distance-pieces **F**,**F**,**F**,**F** interposed. Little cells in the face of **CB** are packed with small granules of carbon **G**,**G**,**G**, which bear against **CD**, and are more or less compressed by it when sound waves impinge on the diaphragm. The receiver **R** is represented by a soft-iron diaphragm **D**, and a soft-iron core **IC**, on which is mounted a coil of several turns of fine wire. The iron core is fixed on one of the poles of a permanent magnet **N S**, and is "polarized" (or magnetized) thereby. The coil is so connected that the current passing through it strengthens the magnetism of the core to a greater or less extent.

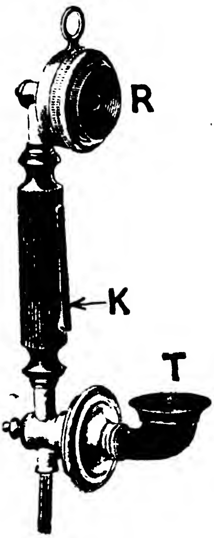


Fig. 119.

The illustration (Fig. 118) is merely diagrammatic, and does not show the actual form of a real transmitter or receiver; in practice arrangements are made for keeping the battery circuit open, except during the short intervals that conversation is taking place.

The slightest movement of **CD** and the variations of compression of the carbon granules **G**,**G**,**G** cause comparatively great variations in the resistance of that portion of the circuit, with corresponding changes in the strength of the current. This is exactly what happens when the diaphragm **CD** is spoken to; and the variations in the current, strengthening the magnet more or less, cause the receiver diaphragm **D** to move in exact correspondence with the movements of **CD**. When **D** vibrates, sound waves are set up in the air which exactly correspond with those at the transmitter end, so that the sounds are reproduced.

112. TELEPHONE CIRCUIT. The form of telephone in ordinary use is depicted in Fig. 119, where **T** is the transmitter and **R** the receiver, the circuit being normally kept open by a key **K**, which is closed when the instrument is clutched in the hand.

When two people are in communication with such instruments, the circuit may be represented as in Fig. 120,

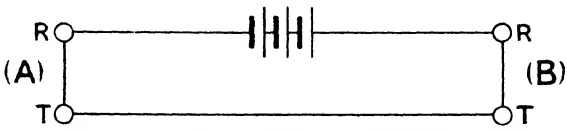


FIG. 120.—DIAGRAM OF REPLY TELEPHONE CIRCUIT.

the two transmitters **T T**, and receivers **R R**, being all in series. If both persons speak at the same time, the effects are naturally mixed-up and confused. But if **A** be speaking to **B**, for instance, the fact that **A** is operating his own receiver as well as **B**'s will make no difference to **A**; while so long as the transmitter at **B** is quiescent

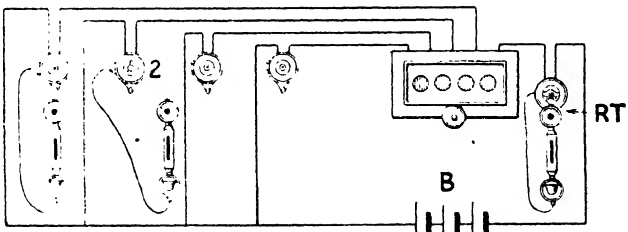


FIG. 121.—COMBINED BELL AND TELEPHONE CIRCUIT.

it will not affect the varying current passing through it from **A**.

Telephones may be easily attached to existing electric-bell systems in such a way as to enable any "room" to call-up and speak with a person wherever the bell may be fixed. Fig. 121 shows how four telephone pushes may be connected with an indicator and a reply telephone **RT** near the latter. Only two of the pushes have telephones attached. When RT is hanging up, and none of the other telephones are touched, the circuit will act as an ordinary bell and indicator circuit. Supposing No. 2 wants to speak, the push is pressed, and the telephone then taken off the hook, this causing the key K (Fig. 119) to be depressed by the hand and the telephone thrown into circuit. The introduction of the two transmitters and receivers into the circuit reduces the current so much that, although it still flows through the bell, it is not strong enough to cause the magnet to attract the armature.

113. KINDS OF CURRENT. In the signalling arrangements so far described a few primary cells have been shown coupled in simple series. Bells, telephones and signalling devices only require small currents. Lamps, heaters and motors take much larger currents, hence many points which one can afford to ignore in the former case cannot be safely overlooked when dealing with higher e.m.f.'s, and greater power in the circuit.

A *secondary battery* is one in which the chemical condition necessary to produce an e.m.f. is produced by passing a current through the battery, a stage called "charging." On being connected in circuit a secondary battery then "discharges," sending a current round the circuit in the opposite direction. As the effect is, broadly speaking, similar to storage of electrical energy, the name storage battery or accumulator is often applied to a secondary battery.

An *alternating current* is one which is constantly reversing its direction at a constant rate, which is usually 25 or 50 times a second. The number of complete reversals per second is termed its frequency or periodicity. The alternating current supplied for lighting and heating purposes is more specifically termed single-phase, to distinguish it from three-phase, which is chiefly used for driving motors.

114. DISTRIBUTION. In every complete or closed electric circuit we have to know the relationship of (*a*) the "rate" at which electricity flows round the circuit, or the current; (*b*) the electromotive force. tension, pressure or voltage on the whole circuit, and the potential difference (p.d.) tending to drive electricity round each portion; (*c*) the resistance of the circuit, and of each of its parts.

As consuming devices are for the most part connected in parallel with one another, it is convenient to join them up to two metal bars, or parallel conductors, at the ends of the supply mains. These bars, together with auxiliary

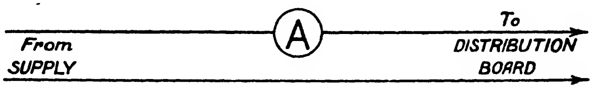


Fig. 122.

safety devices, are designated *distribution boards*; distribution being the splitting up or division of a total current taken from a generator into branches going to the consuming devices.

The term *transmission* is now used where a current is carried a long distance without being split-up or divided;

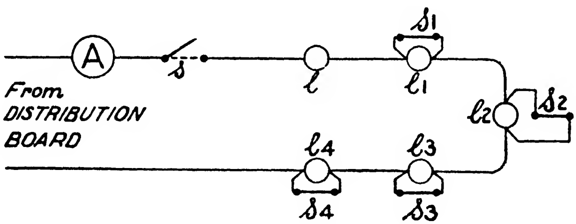


Fig. 123.

thus one transmits energy from one town to another, but distributes it amongst the users in a particular town.

115. CURRENT AND PRESSURE. An *ammeter* is an instrument which shows how much current is passing through a circuit. In their simplest form ammeters are connected direct *in* the circuit and, as they are of low resistance, their presence makes little or no difference to the current. In Fig. 122 an ammeter **A** is shown inserted in one of the conductors to a distribution board, and in Fig. 123 another ammeter **A** is connected to measure the current taken by a number of lamps in series. If the switch *s* be "open," in the full position, the current is cut off. If *s* be "closed," in the dotted position, the current will flow through *l*, the other lamps being shown short-circuited by switches connected in parallel with them. By opening the switches the lamps are brought into the circuit, and if the pressure were varied directly with the number of lamps, the arrangement would be a *constant current* circuit*—a method formerly adopted with arc lamps, and

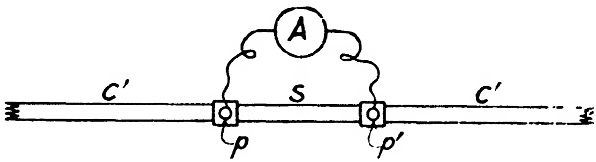


Fig. 124.

still used in special cases to-day for power transmission, particularly on the Continent.

Ammeters are often made to carry only small currents and are then placed in shunt to, or in parallel across, low resistances, as in Fig. 124.

A *voltmeter* is an instrument which indicates the p.d. or pressure or voltage between the two points of a circuit to which it is connected. The circuit itself is not interrupted, the voltmeter and its connecting wires being entirely distinct therefrom. Some voltmeters take considerable current to operate them, or cause their pointers to indicate; others take very little or none, depending upon the principle embodied in their construction.

116. INTERNAL RESISTANCE. A battery has a certain amount of resistance in the liquid between its plates. The liquids used in primary or secondary cells are only semi-conductors, yet their resistance is not sufficiently great to impede seriously the flow of electricity through the battery. In the copper-wire part of the circuit, the

* A circuit in which the current is kept at an unvarying strength under all conditions.

path for the current is a narrow one, but directly the current enters the battery liquid the path becomes a wide one; the large area of the liquid path making up for its relatively bad conducting power. If each cell of a battery had just a thin layer of liquid at the bottom, though the e.m.f. would not be diminished, the resistance would be so enormously increased that the battery would be useless.

The e.m.f. of a primary cell depends simply upon the materials of which it is constructed. Thus a small Leclanché cell would have the same e.m.f. as a large one. The internal resistance of a cell, however, is a very variable quantity depending upon its size, construction, and state of its constituents. The larger the plates and the greater the depth of liquid in the cell, the less will be its internal resistance.

The internal resistance of the ordinary size porous pot Leclanché, under average conditions, is about 1 ohm; and of the ordinary size agglomerate block Leclanché about 0·6 ohm. The resistance of dry cells, which are made in many different sizes, varies from 0·3 to 7 or 8 ohms.

117. DISTINCTION BETWEEN E.M.F. AND P.D. Although e.m.f. and p.d. both signify electrical pressure, there is an important distinction between them. Electromotive force can be spoken of only when we are considering a *source* of e.m.f., and it would be incorrect to talk about the e.m.f. at the terminals of a lamp, or between two points in a circuit. A voltmeter applied to the terminals of a battery giving current would indicate, not the e.m.f. of the battery, but something less than this, viz. the p.d. at its terminals. In some dynamos, and in all batteries, the terminal p.d. varies as the resistance of the external circuit is altered, even though the e.m.f. remains constant. When the generator supplies a current, a certain amount of pressure is taken up in forcing the current through the internal resistance (*internal drop*), and only the difference between it and the e.m.f. remains as the p.d. between the generator terminals.

When a battery or separately-excited dynamo is on open circuit, i.e. when current is not being taken from it, there will be no difference between the e.m.f. and the p.d. on the terminals, and the internal resistance has no effect. Thus certain standards of e.m.f. are cells with a very high internal resistance, but they are only useful where their e.m.f.'s are balanced against other e.m.f.'s without taking a current from them. The pressure of a current generator under these conditions is often spoken of in practice as the *open-circuit* or static *voltage.*

A hot-wire voltmeter takes quite an appreciable current. It could be used with accuracy for measuring the e.m.f. of a secondary cell, as the internal resistance of such a cell is low. It could not be used with equal satisfaction for measuring the e.m.f. of a Leclanché cell because the resistance is much higher, and the mere fact of coupling the voltmeter across the terminals would be to cause the p.d. to be considerably less than the e.m.f. A test taken to illustrate this gave the following figures—

Cell tested.	e.m.f. by potentiometer, which takes no current.	e.m.f. by hot-wire cell testing voltmeter.	difference.
Secondary cell	2·01 v.	2·00 v.	5%
Leclanché ,,	1·48 v.	1·20 v.	16%

118. CELLS IN SERIES AND IN PARALLEL. A battery is a collection of cells generally formed by connecting the + pole of one cell with the – pole of the next, and so on to the end. Cells so arranged are said to be *in series.*

The cells forming a battery need not necessarily be of the same size and type when they are connected in series; though it is not usual for them to differ. The calculation of the e.m.f. of a series connected battery consists simply in adding the e.m.f.'s of the individual cells constituting the battery. The e.m.f. of all cells of the Leclanché type is about 1·5 volts per cell; thus the e.m.f. of a six-cell battery will be 9 volts.

The internal resistance of the battery is equal to the sum of the resistances of each individual cell. If the cells are all alike, and r = the resistance of one cell and there are n cells in series, the total resistance of the battery will $= r \times n$.

The simplest way of joining cells in parallel is to connect all the + poles of the cells together to form one pole, and all the − poles to form the other pole. If a number of similar cells be connected in parallel the e.m.f. of the battery will be that of one cell only. The combined resistance is got by dividing the resistance of a single cell by the number of cells in parallel. If there are p similar cells in parallel the combined resistance of the battery $= r \div p$.

Figs. 125 and 126 show three cells connected in parallel.

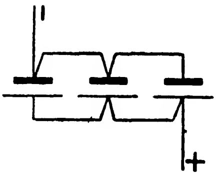


Fig. 125.

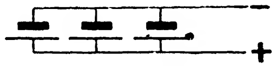


Fig. 126.

Three Cells "in Parallel."

Electrically the diagrams mean the same, but the connections may be drawn in these two ways, or in modifications of them. Only cells of the same e.m.f. may be connected in parallel. Cells of different internal resistances may be connected in parallel, but they will then divide the current between them in inverse proportion to their internal resistances. There is apt to be trouble with different sizes or kinds of cells connected in parallel, due to one part of the battery discharging through another part.

In some stations where a secondary battery becomes too small, a second is added and the two are run in parallel. Each battery should then have a complete set of instruments and regulators, and the parallel connection made outside them so that the current drawn from each battery may be observed: care must be taken to see that the batteries take their proper share of the load, particularly if they happen to be of different sizes.

Intermediate between simple series and simple parallel arrangements are those where the cells are coupled in groups and the groups connected in series or parallel. If the cells in each group are in series, and the groups in parallel, the arrangement is a *parallel-series* one. If the cells in each group are in parallel, and the groups are connected in series, then it is a *series-parallel* arrangement.

To find the e.m.f. and internal resistance of such arrangements, take each group at a time and find the e.m.f. and resistance of the group; then treat the groups as if they were single cells in the battery.

Ex. A battery of 6 cells, each having an e.m.f. of 1·5 volts, and resistance of 1·2 ohms, are arranged in different ways to send a current through an external resistance of 0·50 ohm.

All in series, $E = 6 \times 1{\cdot}5 = 9$ v. and $b = 6 \times 1{\cdot}2 = 7{\cdot}2$ ohms.

$\therefore C = 9/7{\cdot}2 + 0{\cdot}5 = 9/7{\cdot}7 = 1{\cdot}17$ amps.

3 in series and 2 in parallel, $E = 3 \times 1{\cdot}5 = 4{\cdot}5$ v, and $b = 3 \times 1{\cdot}2/2 = 1{\cdot}8$ ohms.

$\therefore C = 4{\cdot}5/1{\cdot}8 + 0{\cdot}5 = 4{\cdot}5/2{\cdot}3 = 1{\cdot}96$ amps.

2 in series and 3 in parallel, $E = 2 \times 1{\cdot}5 = 3{\cdot}0$ v., and $b = 1{\cdot}2 \times 2/3 = 0{\cdot}8$ ohm.

$\therefore C = 3/0{\cdot}8 + {\cdot}5 = 3/1{\cdot}3 = 2{\cdot}31$ amps.

All in parallel, $E = 1{\cdot}5$ v. and $b = 1{\cdot}2/6 = 0{\cdot}2$ ohm.

$\therefore C = 1{\cdot}5/0{\cdot}2 + 0{\cdot}5 = 1{\cdot}5/0{\cdot}7 = 2{\cdot}14$ amps.

119. MAXIMUM POWER. A battery circuit is a complete circuit since it contains the actual source of e.m.f. The resistance of such a circuit is made up of the internal resistance of the battery and the external resistance, or that of the apparatus through which the current is sent together with connecting wires.

In such a circuit—

$$\text{Current} = \frac{\text{e.m.f. of battery}}{\text{resistance of battery + external resistance}}$$

$$= \frac{\text{p.d. on battery terminals}}{\text{external resistance}}$$

$$= \frac{\text{internal drop}}{\text{internal resistance}}$$

The same statement applies to a dynamo if of the magneto type. But it is one of the properties of an ordinary dynamo that its e.m.f. has not a fixed value, like that of a battery, but can be altered by weakening or strengthening the electro-magnet which, in such a machine, takes the place of the permanent magnets of a magneto machine. Hence for illustrative purposes we will consider batteries only.

Ex. (*a*). Two wires in parallel, which have resistances of 2 and 4 ohms respectively, are connected to the terminals of a battery whose e.m.f. is 6 volts and internal resistance 1 ohm. *Find current in each resistance.*

$$\text{Joint resistance} = \frac{2 \times 4}{2 + 4} = \frac{8}{6}\ \text{ohms; add 1 ohm} = \frac{14}{6}\ \text{ohms.}$$

$$\text{Current} = \frac{6}{14/6} = \frac{6 \times 6}{14} = \frac{36}{14} = 2\frac{4}{7}\ \text{amps.}$$

Current splits in inverse proportion to resistances,

$$\therefore C \text{ in 2 ohm wire} = \frac{4}{6} \times \frac{36}{14} = \frac{12}{7} = 1\frac{5}{7}\ \text{amps.}$$

$$\text{and } C \text{ in 4 ohm wire} = \frac{2}{6} \times \frac{36}{14} = \frac{6}{7}\ \text{,,}$$

$$\text{making up total of}\qquad 2\frac{4}{7}\ \text{,,}$$

Ex. (*b*). A battery of 10 volts and 0·23 ohm internal resistance is supplying current to three parallel circuits having respectively 2, 3, and 4 ohms resistance. What will be the power in each of the three circuits ?

$$\text{Ext. res.} = \frac{1}{0{\cdot}5 + 0{\cdot}333 + 0{\cdot}25} = \frac{1}{1{\cdot}083} = 0{\cdot}923\ \text{ohm.}$$

$$C = \frac{10}{0{\cdot}23 + 0{\cdot}923} = \frac{10}{1{\cdot}153} = 8{\cdot}67\ \text{amps.}$$

p.d. lost in battery = $8{\cdot}67 \times 0{\cdot}23 = 1{\cdot}99$ volts.

p.d. on battery terminals = $10 - 1{\cdot}99 = 8{\cdot}01$ volts.

power delivered to external circuit = $8{\cdot}01 \times 8{\cdot}67 = 69{\cdot}41$ watts.

This divides in proportion of conductances—

2ω circuit	= 0·5 mho	= 0·5 × 69·41/1·083	= 32·05	watts.
3ω ,,	= 0·333 ,,	= 0·333 ,, ,,	= 21·34	,,
4ω ,,	= 0·25 ,,	= 0·25 ,, ,,	= 16·02	,,
Total power delivered to external circuit			= 69·41	,,
Power lost in battery = 1·99 × 8·67			= 17·29	,,

Total power produced by the battery = 10 × 8·67 = 86·70 watts.

This example represents on a small scale what happens on a large scale in electricity supply. If it were worth while, a similar balance sheet could be prepared showing the power in each part of a supply system with any particular total power which at a certain time might be generated.

When the external resistance in a circuit is great as compared with the internal resistance of the battery the cells need not be very large but there should be plenty of them, and they should be connected in series so that the e.m.f. of the battery is as high as possible. When the external resistance is not great, the internal resistance of the battery becomes of consequence, and must be kept down by using a few large cells.

When the external resistance is very small indeed, the only way to get a large current with primary cells is to adopt a parallel-series or parallel-combination. If the cells had each a considerable internal resistance, it would be of no use increasing the number in series, as although the e.m.f. would be increased, the total resistance of the circuit would be increased at practically the same rate, and the current would consequently hardly be increased at all.

A battery gives the *highest p.d.* on its terminals when on open circuit, then the p.d. = e.m.f. The resistance of the external circuit is then infinite.

A battery gives its *largest current* on short circuit, then the p.d. = *o* ; all the e.m.f. being taken up in forcing the current through the internal resistance. The resistance of the external circuit is then infinitesimal.

To obtain the *maximum power* developed in the external circuit, the arrangement of cells should be such that the **internal resistance is equal to the external resistance,** or as near this as possible.

Ex. (*c*). Twelve cells of 1·5 volts and 1 ohm each could be joined up in six different ways to send current through an external resistance of 3/4 ohm; all in series, two parallels of six, three of four, four of three, six of two, or all in parallel. The results would be—

e.m.f. volts.	Internal res. ohms.	Total res. ohms.	Current, amps.	Power, watts.
18	12	12·75	1·41	1·50 Simple series.
9	3	3·75	2·4	4·32
6	1·33	2·083	2·88	6·22
4·5	·75	1·5	3·0	6·75 (Internal and external resistances equal).
3	·333	1·083	2·77	5·76
1·5	·083	·833	1·80	2·43 simple parallel.

The greatest power is developed in the external circuit when the internal and external resistances are equal, but it must be noted that this is only half of the total power, i.e. the other half is absorbed in the battery. Under these conditions the maximum current is obtained in the circuit. This is not the maximum current the battery could give, which is the current on short-circuit; but it is the maximum that particular number of cells, however grouped, could give with that particular resistance in the external circuit.

120. SHORT CIRCUIT. If the terminals of any apparatus be connected across by a short piece of copper wire, no current would pass through the apparatus when inserted in a circuit in which current was flowing.

The apparatus is said to be short-circuited, or "shorted." It is shunted by such a low resistance that the current would practically all flow through the easy path provided by the short-circuiting wire. If an electric lamp or motor happens to be the apparatus in question and the circuit switch be closed, the fuses on the circuit would be "blown" at once by the heavy current which would endeavour to flow through the short circuit.

The effect of short-circuiting is illustrated in Fig. 127 by considering two branches *a* and *b* in a circuit. Suppose *a* has a resistance of, say, 10 ohms and *b* a resistance of

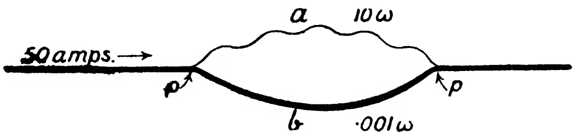


FIG. 127.

0·001 ohm ; *b* consequently represents a short-circuit path, as practically all the current will flow through it.

If the current in the circuit be 50 amps., then—

Resistance of	Conductance of	Current
a = 10 ohms	= 0·1 mho	1/10001 of 50 amps. = 0·005 amps.
b = 0·001 ohm	= 1000·0 mhos	10000/10001 of 50 amps. = 49·995 amps.

Another way of explaining the matter is to say that the connection of *b* at the points *pp* reduces the p.d.

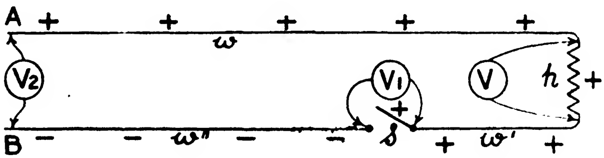


FIG. 128.

between these points to such a low figure that practically no pressure is available for forcing current through *a*.

121. OPEN CIRCUIT. Before a circuit is closed, say at a switch, the full difference of potential, equal to the e.m.f. on the circuit, exists between the contacts of the switch. This is also the difference at the moment the circuit is opened.

In a circuit containing a heater *h*, or other consuming device, and a switch *s*, if three voltmeters were joined as in Fig. 128 when the switch is closed, **V** would indicate practically the full pressure on the circuit ; the same pressure, in fact, as at V_2. On the other hand, V_1 would indicate nothing at all. When the switch is open, the indication on V would drop to zero, while V_1 would show nearly—if not quite—the full pressure on the circuit, if its resistance be very high compared with that of *h*. There is practically no current flowing, and therefore no voltage drop round the circuit.

The wire connected to the + terminal (with everything connected in it) takes the potential of that terminal: and the other wire between the – terminal and the switch (with everything connected in it) takes the potential of that terminal. That is to say, when the switch is opened, by far the greatest portion of the resistance in the circuit is that of the voltmeter itself, and it is there consequently that nearly the whole drop of pressure takes place.

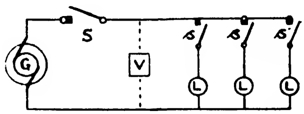


FIG. 129.

If the voltmeter be of the electrostatic type, it will indicate quite the full pressure when the switch is open. If it be of the usual wire-wound type the greater its resistance as compared with that of the wires and everything connected with them (together forming the " circuit "), the nearer will its indication approach the full voltage.

A point to be noted is that an ordinary voltmeter is electrically simply a resistance, though a high one. If a 500-volt dynamo *G* were running and it was desired to do some repairs to the main switch, Fig. 129, all the switches *S*, *s*, would be opened, switching off the lamps L. It would be assumed to be perfectly safe to make the repairs. But if a voltmeter, as at V, remained in circuit, then anyone touching the two terminals of *S* might receive a fatal shock. The pressure across his body would depend upon its resistance compared with that of V, these two resistances being in series, and in circuit with the 500 volts.

A shock is sometimes got from points on the same side or pole of a distribution board. In Fig. 130 on D the switches control the + poles. When both are on, they and the wire *w w'*, leading to the lamps *l l'*, will be positively charged. But if, say, *s'* be opened, the potential of the wire *w'* will immediately drop to that of the negative bus-bar, and the full pressure will exist between the bottom terminals of *s'* and *s*. The resistance of the human body is so very much greater than that of the lamp *l'*, that anyone touching these two points would receive a shock at a pressure very nearly equal to the voltage of

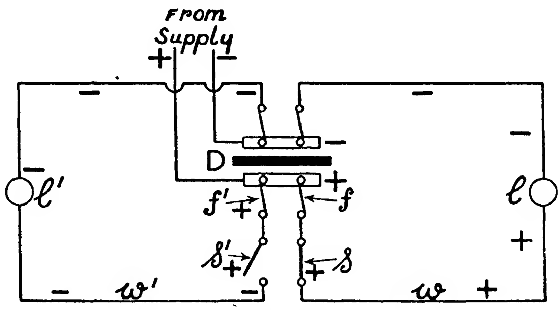


FIG. 130.

supply. Hence the Home Office rule that every motor, etc., shall be protected by efficient means so connected that *all pressure* may thereby be cut off from the motor and all apparatus in connection therewith; which means that a double-pole switch should be used, cutting both leads.

122. ELECTRICAL PRESSURE means the difference of electrical potential between any two conductors, or between a conductor and earth as read by a hot-wire or electrostatic voltmeter.

If the circuit be open, then between the terminals of the circuit where the break occurs the full e.m.f. will exist.

If the circuit be closed and a current flowing round it, then we may regard the e.m.f. to be generated in one part of the circuit and be absorbed in the remainder, the absorption being equal to the different pressure-drops or falls of potential, which in the aggregate must be equal to the e.m.f. It is like an example in book-keeping—

Dr. side		*Cr. side*
e.m.f.	=	$pd_1 + pd_2 + pd_3$, and so on.

Where consumers obtain electrical energy from street mains there is no actual e.m.f., except at the generating station. The pressure on the consumer's circuit is due to the potential difference between the two mains at the point where they enter his premises, by what is known as the service line.

It is first rather puzzling to find that when one lamp in an installation is turned on it does not get too much pressure; and that when a number of lamps are switched on, the pressure does not fall and the lamps burn rather dim. The explanation is that the pressure is so high compared with the loss of pressure in the leads between the generator and the lamps, that the variation in the loss should not be sufficient to make any *material* difference. Moreover, the pressure on street mains, or at some point in the centre of a private installation, is kept constant (or nearly so) under all conditions by control of the machinery at the distant generating station.

It is very necessary that lamps, heaters, and motors on a consumer's premises should be suited to the particular supply pressure available.

If the pressure be lower than that specified for the apparatus, the lamps will burn more or less dimly, the effectiveness of the heaters will be diminished, and the power of the motors reduced. The reason in each case for the lessened effect is that the current through the apparatus is smaller than it is designed to work with.

If the things are connected to too high a pressure the currents will be greater than they should be. The lamps will certainly burn very brightly, but they will not last so long. The heaters and motors also will give out more heat and power respectively; but both will be liable to over-heating and damage.

123. CLOSED CIRCUIT. The effect of resistance in a circuit is to cause a fall of potential round the circuit. In Fig. 131 a battery, B C, of 2 volts e.m.f. and 4 ohms internal resistance is connected to earth at B, so that the potential of its negative terminal is zero. It is joined up to a circuit consisting of 4 ohms between C and A and 8 ohms between B and D: between these, at A D a switch is interposed. The dotted line, or curve, in Fig. 132 shows the distribution of potentials when A D is open, and the full line what it is when the switch is closed. Below the diagram the circuit is drawn, stretched out, and the lengths made proportional to the resistances. It

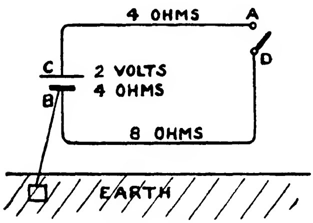


FIG. 131.

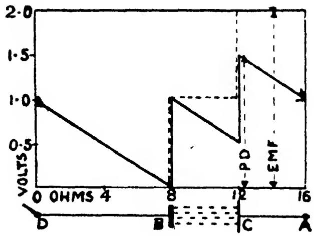


FIG. 132.

must be understood that A and D come together when the switch is closed, just as if the diagram were wound round a cylinder with the left and right-hand edges coinciding.

124. PRESSURE DROP. A simple circuit comprises a generator, positive lead, consuming devices, and return lead to the generator. The e.m.f. in the circuit is taken up in sending a current C through these four parts.

When the circuit is closed through leads of appreciable resistance, there will be less pressure V (Fig. 128) at the consuming devices than the full pressure of the circuit V_2 at the supply end. This difference is due to the pressure-drop in the leads, and the difference between the pressures at these two points becomes greater as the current through the leads increases. The consuming devices form the principal resistance in the circuit, and consequently most of the loss of volts takes place in them. What C will be must depend on the pressure **V** across the terminals of the consuming devices. The pressure at their terminals gets less and less as more are added, and the current through each decreases.

The loss of pressure V_3 in the leads is measured by the *difference* in the pressures across the terminals of the generator and across the consuming device, i.e. $V_3 = V_2 - V$. The fall of potential in the leads is variously termed "pressure-drop," "drop in volts," "lost volts," or simply

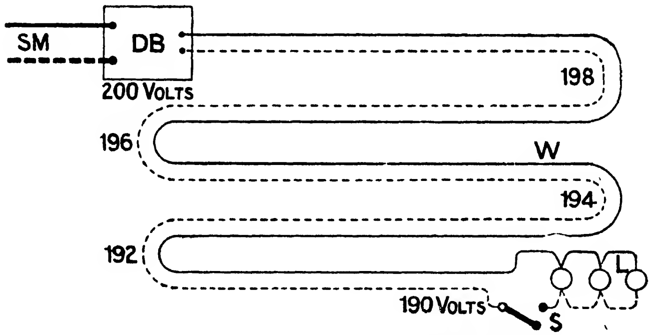


FIG. 133.—PRESSURE DROP ALONG A CIRCUIT.

"drop." The pressure-drop in a part of a circuit is proportional to its resistance and to the current passing through. This is nothing more than the application of Ohm's law to part of a circuit, but it is one of these applications which is not always obvious.

In Fig. 133 a street main **SM** supplies a distribution board **DB** at 200 volts, and from this a pair of very long wires **W** form a circuit to a switch **S** and group of lamps **L**. The pressure gradually decreases on the way to the lamps and, with a current density of 1,000 amps. per sq. in., if the distance be about 200 yds. the p.d. across the lamps would be only 190 volts.

A good illustration of what is meant by pressure-drop is obtained by placing a 100-volt carbon-filament lamp, say of 8 c.p. L, in series with a resistance R, across a 110-volts supply, Fig. 134. On applying an ordinary voltmeter V between the lamp terminals to ascertain whether the pressure is correct the light diminishes.

When the lamp is in circuit alone, the 110 volts would be divided, say, in the proportion of 100 volts across the lamp and 10 volts across the resistance. Connecting the voltmeter V in parallel with the lamp reduces the total resistance of the circuit, causing more current to flow through R, which then absorbs more than 10 volts. This reduces the pressure on the terminals of the lamp which therefore gives less light.

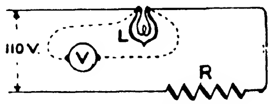


Fig. 134.

It should be noted that an accurate voltmeter will indicate correctly the pressure across L, although its reading will not be the original pressure but that existing under the modified conditions. Therefore it is necessary to know exactly what change is brought about by adding an instrument. One seeks to measure all such quantities as they exist under normal conditions, and the most suitable method of measurement is that which does *not* alter the quantity to be measured by the mere act of measuring it.

(i) *Drop is Proportional to Current.* If the resistance of a conductor remains constant, then the pressure-drop in it increases as the current through it increases. Hence the available pressure at the consumer's end of the main on a supply system would fall as the current taken is increased. To prevent this the custom is to raise the pressure at the generating station end as the load comes on. On very long mains pressure is added to that on the bus-bars of the station by passing the current through "boosters" which add as many volts as may be necessary to make up for the pressure-drop on these long mains.

Attempts made in the early days of supply to "zone" the pressures (stating that near the station the pressure would be 110 volts, farther away 105, and in outlying districts 100 volts) failed for the reason that at light loads, and when little current was being taken, the pressure was practically the same all over the area supplied. What was correct at full loads, with heavy currents in the mains, could not be equally so with small currents.

Ex. (*a*). A pair of cables, forming a main, supply 350 amps. to a distributing box 100 yds. away, from the generator and the drop in the cables is 5 volts. If the current were reduced to 225 amps. the drop would be—

$$\text{Since } R = \frac{e}{c} = \frac{e'}{c'} \therefore e' = \frac{c'}{c} \times e$$

$$\text{or } e' = \frac{225 \text{ amps.}}{350 \text{ amps.}} \times 5 \text{ volts} = 3{\cdot}214 \text{ volts.}$$

It should be noted that the length does not enter into the problem.

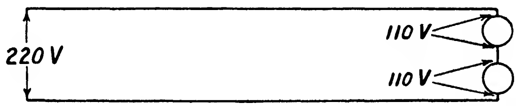


FIG. 135.

In a circuit composed of a wire of the same material and diameter throughout, the pressure falls uniformly round the circuit, that is (ii) the *drop is proportional to length.*

Ex. (*b*). The pressure-drop in 160 yds. of a given cable is 2·7 volts with 56 amps. Find drop in 75 yds. with 90 amps.

$$\text{Drop} = \frac{75}{160} \times \frac{90}{56} \times 2{\cdot}7 = 2{\cdot}04 \text{ volts.}$$

If two lamps of similar resistance are connected in series on a 220-volt circuit, as in Fig. 135, and the leads connecting them are of negligible resistance compared to the lamps, the pressure across each lamp would be 110 volts. This was the method employed to run metal lamps when they were only made for voltages of about half the ordinary supply pressures. Lamps joined up in this way must be matched for current, i.e. they must give their full light with the same amperes through each, and not for voltage.

Three-wire systems of supply have the lamps, etc., in consumers' premises connected in this way, but it cannot be expected that different premises will take the same current, so the excess of current from one consumer as compared with another is taken back to the supply station from the intermediate junction, thus maintaining an approximate equality of pressure on each side of that junction.

(iii) *The drop in volts along a conductor = resistance of conductor × current in conductor.* With a *constant pressure* on the terminals of a supply system, and with leads of small resistance relatively to the resistance of the appliances connected by such leads, it makes little difference in the current through a small consuming device, such as a lamp, whether one or several more with it, are connected at the ends of the leads. The larger the number to be connected, the less resistance should there be in the leads.

Ex. (*c*). Ten lamps, each taking 56 watts, have to be supplied with 220 volts at a distance of 50 yds. from a distribution board through 7/0·028 cables. Find drop of pressure in the cables.

$$\text{Current} = \frac{\text{watts}}{\text{volts}} = \frac{10 \times 56}{220} = 2{\cdot}54 \text{ amps.}$$

$$\text{Length of cables} = \text{Twice } 50 \text{ yds.} \times 36 = 3600 \text{ in.}$$

$$\text{Resistance} \;,, \; = \frac{L}{a}\rho = \frac{3600 \times 0{\cdot}000{,}000{,}66}{7 \times (0{\cdot}7854 \times 0{\cdot}028 \times 0{\cdot}028)} = 0{\cdot}55 \text{ ohm.}$$

$$\text{Pressure drop} = C \times R = 2{\cdot}54 \times 0{\cdot}55 = 1{\cdot}4 \text{ volts.}$$

Note, the length of cables is that of lead and return, so conductor length is twice the circuit length. It is a common error to overlook this.

Ex. (*d*). A dynamo supplies 100 lamps of 220 volts, each taking 0·2 amp., half-a-mile away through 0·04 sq. in. cables. Find dynamo p.d.

$$\text{Current} = 100 \times 0{\cdot}2 = 20 \text{ amps.}$$

$$\text{Length} = 0{\cdot}5 \times 2 \times 1760 \times 36 = 63{,}360 \text{ in.}$$

$$\text{Resistance} = \frac{63{,}360 \times 0{\cdot}000{,}000{,}66}{0{\cdot}04} = \frac{0{\cdot}04181}{0{\cdot}04} = 1{\cdot}045 \text{ ohm.}$$

$$\text{Drop } C \times R = 20 \times 1{\cdot}045 = 20{\cdot}9 \text{ volts.}$$

$$\text{Pressure on lamps} = 220{\cdot}0 \;,,$$

$$\text{p.d. on dynamo} = 240{\cdot}9 \;,,$$

(iv) *Resistance of conductor = drop along conductor ÷ current through conductor.*

Ex. (*e*). A dynamo supplies 30 amps. to a distribution board 250 yds. away. Find the area of cable for a drop of 5 volts.

$$\text{The resistance} = \frac{5}{30} = 0{\cdot}17 \text{ ohm.}$$

$$\text{and } A = \frac{500 \times 36}{0{\cdot}17} \times {\cdot}000{,}000{,}66 = 0{\cdot}07 \text{ sq. in.}$$

Ex. (*f*). Ten 60-watt lamps are supplied at 110 volts 90 ft. from a distribution board. Find diameter of conductor giving a pressure drop of 1·1 volts.

Current = 10 × 60/110 = 5·45 amp.

Resistance of conductor = drop/current = 1·1/5·45 = 0·202 ohm.

" " " also = $L \times \rho/A$

∴ area " " " = (2 × 90 × 12) × 0·000,000,66/0·202

" " " " = 0·00707 sq. in.

" " " " = 0·7854 × d^2

∴ d^2 = area /0·7854 = 0·00707/0·7854 = 0·009

and $d = \sqrt{0{\cdot}009}$ = 0·0949 in. diameter.

125. CONDUCTORS may consist either of a single wire, or of a number of wires stranded or twisted up together. "Flexible cords" are made up of a comparatively large number of fine copper wires or "strands," for the sole reason that they have to be very flexible. Blades of large switches are made up of leaves or "laminae," in order that each may take a bearing, or "bed," upon the contacts, and that the whole may possess the attribute of springiness or elasticity. Some students seem to think that the object in these cases is to reduce the resistance of the conductor. This is quite a mistake; the same weight of metal made up into leaves or fine wires of the same length as a solid bar or copper rod will have the same resistance, neglecting the small effect that may be introduced by the rolling or drawing slightly altering the physical nature of the material.

The sizes of wires used to be given by designating the Standard Wire Gauge. It is now customary to give the diameter of each wire forming a strand and the number of strands, and to refer to large cables by the cross-sectional area in sq. ins.

Varying numbers of separate wires are shown, for the different *typical* sizes, in the following table—

Area. sq. ins.	Number (of wires comprising conductor).	Diameter (of wires comprising conductor).	Overall diameter of conductor.	Resistance per 1000 yds. 60° F. in ohms.
0·001	1	0·036 in.	0·036 in.	23·59
0·002	3	0·029 ,,	0·062 ,,	12·36
0·0045	7	0·029 ,,	0·087 ,,	5·28
0·03	19	0·044 ,,	0·220 ,,	0·85
0·12	37	0·064 ,,	0·448 ,,	0·21
0·4	61	0·093 ,,	0·837 ,,	0·06
0·6	91	0·093 ,,	1·023 ,,	0·04
0·85	127	0·093 ,,	1·209 ,,	0·03

Those particular numbers are chosen as they permit of any size of wire being packed or twisted together into circular shape. There are some fifty different regular sizes of stranded copper conductor, the largest of which are capable of carrying 1,000 amps. In practice these very heavy cables become unwieldy, and it is better to take the current, say, from a large alternator by a number of cables in parallel than to rely upon one of the same area, It is then easier to make satisfactory joints, and the copper is used to greater advantage.

The smaller sized conductors are employed in wiring ordinary buildings. When a certain current has to be provided for, one naturally chooses the smallest possible size of wire or cable in order to keep down the cost. There are limits to the smallness of conductors, such as mechanical strength and permissible pressure-drop apart from their nominal current-carrying capacity. Thus the Institute of Electrical Engineers regulations will not permit of a smaller size of flexible cord than the equivalent of 0·0006 sq. in. Apart from flexible, and wire for use in the wiring of fittings, no conductor smaller than 0·0015 sq. in. may be used. Further, no larger single wire than 0·003 sq. in. is permissible.

The length of each wire in a stranded conductor made up of a number of wires is about 2 per cent in excess of the length of the conductor as all the wires, with the exception of the central one, have a spiral path. Consequently the resistance of the stranded conductor is this amount greater than would be the case if the same cross-sectional area were in the form of a solid wire. The current flows along each separate wire; the relatively poor contact between the strands rendering this the shortest electrical path.

For terminals, and certain other parts of electrical apparatus, brass forms a more convenient conductor than copper, as it can be easily cast, stamped, or worked into any required shape.

Platinum is only used for leading the current through glass, when this material forms a bulb or wall, as its expansion with heat is very nearly the same as glass. It is also used for the contact tips of bells and relays, owing to its extreme freedom from oxidation, and its power of withstanding the burning or wearing action of electrical sparking.

Tin and lead, or alloys thereof, are frequently used for small current fuses, those for large currents being generally made of tinned copper, zinc, or aluminium. For reliability, where the currents are small, silver has proved very satisfactory as a fuse-wire, and is so employed frequently in Continental practice.

Tungsten is a metal whose comparatively high resistance and other special properties have rendered it suitable for the filaments of incandescent lamps.

Mercury, being a liquid metal, is sometimes employed for making connection between fixed and moving, or movable, parts of a circuit.

126. CURRENT DENSITY. (v) *The current in a conductor = drop in volts along the conductor ÷ resistance of conductor.*

Different currents can be sent through a conductor of a given cross-sectional area by using different potential differences across its ends. A direct current may be said to flow equally through each portion of the section, or to permeate the conductor. To define the proportion of the current to the area through which it flows, the term current-density is used ; just as one is accustomed to speak of density of population in persons living *per* square mile, or as the engineer talks of pressures *per* square inch—

$$\text{Current-density} = \frac{\text{current in conductor}}{\text{sectional area of conductor in sq. in.}} = \frac{C}{A}$$

The loss in a conductor is proportional to the current-density, and if the conductor be made of copper the pressure-drop will be for a current-density of 1,000 amperes per square inch—

$$C \times R = \frac{C}{A} \times L \times \rho = \frac{CL\rho}{A} = \frac{1000 \times 63{,}360 \times 0\cdot000{,}000{,}66}{1}$$

$$= 42\cdot42 \text{ volts per mile of single conductor.}$$

A circuit comprises lead and return conductors, therefore the pressure-drop will be = 84·48 volts per mile of *circuit*. To allow for joints the common figure to memorize is, that with a current density of 1,000 amps. per sq. in. the pressure-drop is—

	for a length of, or,
88 volts.	per mile } of copper-circuit.
5 volts.	per 100 yds. } of copper-circuit.

The old " cricket-pitch rule " agrees with this. To score " one run " one batsman has to cover 22 yds., and the other batsman also 22 yds. in the opposite direction. The pressure-drop in 22 yds. of circuit is about 1 volt. This does not allow anything for joints, and it is easy to remember **5 volts per 100 yds. of circuit at 1,000 amps. per sq. in.** as the simple rule dealing with copper-drop.

A rapid means of checking calculations is to work out pressure-drop and see if this agrees with the current-density figure given above.

$$\text{Since } R = \frac{L}{A}\rho = \frac{E}{C}$$

it follows, drop = current density × length × k.

Where k = a constant, depending upon the metal of which the conductor is composed. If the length is taken in hundreds of yards, then $k = 0{\cdot}005$ for copper.

Ex. (*a*). A main ½ mile circuit length is worked at 520 amps. per sq. in. Find drop.

Drop $= 520 \times 8{\cdot}8 \times {\cdot}005 = 22{\cdot}88$ volts.

Ex. (*b*). A feeder (i.e. pair of cables) 3,600 yds. long and 0·2 sq. in section carries 180 amps. at full load. Find lost volts.

At 1,000 amps. per sq. in.; drop $= 5 \times 36 = 180$ volts.

Note, that if there is 1 volt drop for each ampere through the feeder, it must have one ohm resistance.

At 900 amps. per sq. in., as given; drop $= 180 \times 0{\cdot}9 = 162$ volts.

Ex. (*c*). A pair of long cables, starting from 500 volt bus-bars, run side by side and carry their full current at 1,000 amps. per sq. in., but it appears the current is short-circuiting between them somewhere. How far away is the short-circuit ?

This can be answered by mental arithmetic—10,000 yds.

If a number of wires of different areas, but made of the same material, are connected in parallel between terminals or bus-bars having a difference of potential, the currents will be proportional to the areas of the wires and therefore the current-densities will be the same. The wires are of the same length.

The current-density $= \dfrac{C}{A}$ and since $R = \dfrac{L}{A}\rho \;\therefore\; A = \dfrac{L\rho}{R}$

or $\dfrac{C}{\dfrac{L\rho}{R}} = \dfrac{CR}{L\rho} = \dfrac{E}{L\rho} =$ a constant, and, since E, L and ρ are constants, hence $\dfrac{C_1}{A_1} = \dfrac{C_2}{A_2} = \dfrac{C_3}{A_3}$, and so on.

Ex. (*d*). If three copper-conductors of 0·025, 0·050, and 0·075 sq. in. section, each 1,000 yds. long, were connected in parallel between two bars between which there was a pressure of 24 volts, then, working out the resistances in the same way as other examples—

Area.	Resistance.	Current.	Pressure drop.	Current-density.
0·025 sq. in.	0·96 ohm	25 amps.	24 volts	1000 amps. per sq.in.
0·050 ,,	0·48 ,,	50 ,,	24 ,,	1000 ,, ,, ,,
0·075 ,,	0·32 ,,	75 ,,	24 ,,	1000 ,, ,, ,,

thus illustrating the statement made above.

127. POWER LOSS. (vi) *The power lost in a conductor = current in conductor × drop in volts along the conductor.* The greater the current-density in a given conductor the greater will be the power lost in it. The pressure-drop in cables, supplying a consuming device, means a loss of power, so that we can express this loss as a proportion of the total power taken from the source.

Ex. (*a*). A transmission line consists of two wires, each 2 kms. long and 150 sq. mm. area, and carries 150 amps. $\rho = 1{\cdot}72$ microhms per cm. cube. Find power wasted in the line.

$$R = \frac{2 \times 2 \text{ kms.} \times 1000 \times 100}{1{\cdot}5 \text{ sq. cm.}} \times 0{\cdot}000{,}001{,}72 = 0{\cdot}4587\omega$$

Power lost $= 150^2 \times 0{\cdot}4587 = 10{,}320$ watts.

NOTE.—A density of 1 amp. per sq. m.m. = 645 amps. per sq. in.

Ex. (*b*). 200 kws. are delivered 1 mile from a power station. The supplied pressure is 1,000 volts, and the efficiency of transmission is 90%. $\rho = 0{\cdot}69$ microhms per inch cube. Find area of the line.

At 1000 volts, each amp. = 1 kw. ∴ current = 200 amps.

Pressure at power station	=	100 × 1000/90 =	1111·1 volts.
Drop on line	=	10 × 1000/90 =	111·1 ,,
Pressure at receiving end	=		1000·0 ,,

$$\text{Area of line} = \frac{L\rho}{R} = \frac{(2 \times 1760 \times 36) \times 0{\cdot}000{,}000{,}69}{0{\cdot}5555}$$
$$= 0{\cdot}157 \text{ sq. in.}$$

NOTE.—At 1,000 amps. density the cable would carry 157 amps. and lose 88 volts in the mile: it actually carries 200 amps, which is a density of 1,271 amps. per sq. in., so to check the working compare drops with densities, i.e. $\frac{200}{157{\cdot}4} \times 88 = 111{\cdot}8$ which proves above.

Ex. (*c*). A feeder line has to supply 100 kws. at 440 volts, at a distance of half a mile from a generating station. The loss is 6% of the power put into the feeder. The resistance of a bar of copper 1 ft. long and 1 sq. in. section is 7·9 microhms. Find area of feeder.

Current through line = 100,000 watts/440 = 227·3 amps.

Power, P, lost in line $= 6 \times 100/94 = 6{\cdot}38$ kw. $= C^2R$

∴ R of line $= P/C^2 = 6380$ watts$/227{\cdot}3^2 = 0{\cdot}1236$ ohms.

The res. of	1 ft. 1 in. sq. = 7·9 microhms	= 0·000,007,9 ohms.
,, ,, ,,	5280 ,, ,,	= 0·041,712
but ,, ,,	line	= 0·1236

∴ area ,, ,, = 0·041,712/0·1236 = 0·3375 sq. in.

NOTE.—This is a practical case, as the power delivered is stated and power required to be put into the line has to be found. Thus with 227·3 amps. through an area of 0·3375 sq. in. conductor, the current density is 673·3 amps. per sq. in. and—

	At generating station.	Loss on line.	At receiving end.
the pressure is	468 volts	28 volts	440 volts
the power is	106·38 kw.	6·38 kw.	100 kw.

On half-a-mile of circuit, at 1,000 amps. per sq. in. density 44 volts would be lost. The density is about ⅔rds of this, so the drop is only 28 volts.

The res. of the line can be checked by—

$$\frac{\text{drop}}{\text{current}} = \frac{28}{227 \cdot 3} = \frac{L \times \rho}{A} = \frac{63{,}360 \times 0 \cdot 000{,}000{,}658}{0 \cdot 3375} = 0 \cdot 1236 \text{ ohm.}$$

128. ENERGY LOSS in a conductor depends upon the power loss, and the time that loss continues. The current through a main is seldom steady for any lengthy period, so it is not quite so simple to calculate energy loss; but if each steady period be taken and its loss ascertained, the sum of all these losses will give the total loss for the aggregate period. It is in this way that the energy loss on a large system, being designed, is predicted. In the last example, if the load remained at its full value for 1,500 hours in the year, at half for 600 hours, and at one quarter for the rest of the factory hours, say 2,400 hours per annum, while the load was entirely off for the remainder of the year, the energy lost or wasted in the line per annum would be as follows—

Load supplied kws.	For hours.	Energy supplied units.	Current amps.	Loss in line kws.	Units lost in line.
100	1,500	150,000	227·3	6·38	9,570
50	600	30,000	113·6	1·595	957
25	300	7,500	56·8	·399	119·7
Total units supplied	=	187,500	Total units lost	=	10,646·7

It follows that in designing a line a larger full load loss is permissible if the full load has not to be carried for lengthy periods, while a smaller full load loss is arranged for if the line has to be worked at or near full load continuously. Further, if the cost of a unit be high, then the loss should be kept down by spending more money on a larger line, while, if a unit can be generated cheaply, the first cost can be minimized by permitting a heavier line loss.

What is commonly known as Kelvin's law is a statement to the effect that the total cost of transmitting electrical energy by a line is least when the annual value of the energy lost in the line is equal to the annual value of the interest on the capital expended on the line. This has to be modified in practice because the cost of a line is not all put into the conductor but includes the price paid for supporting or protecting, and insulating the conductor. Broadly, however, it means what has already been explained. A large line costs more money naturally, but wastes less than a smaller one which is less expensive to buy. Capital invested, or money spent, in buying a conducting line, represents an annual expenditure in interest paid to the lender of the money, what is commonly called "the value of money." Units wasted in the line represent a certain sum of money paid for these units. When these two amounts are equal, then the most economical condition has been found.

129. HEATING OF CONDUCTORS. The heat developed in a wire by a given current in a given time is simply proportional to the resistance of the wire. In order to get plenty of resistance in a wire without its having to be very long or very thin, it must be composed of a metal or alloy that has a high resistivity; and if it be desired to heat the wire to a high temperature, its material must have a high melting point.

The metal filament of a lamp *l*, connected by copper wires *w w*, and a switch *s*, to the bus-bars *b*, of a distribution board in Fig. 136 will get white-hot, while the wires leading to it remain practically cold. The filament of the lamp is much thinner than the connecting wires, and the filament is of tungsten, which has a much greater resistivity than copper.

In a direct-current circuit in which there is no back e.m.f., nothing but heat (with or without light) will be developed. With a uniform metallic circuit, the pressure drops gradually from one end to the other, and the development of heat will be spread evenly over the whole circuit, so to speak. In Fig. 136 there is little drop of pressure along the wires *w w*, practically the whole of it taking place in the lamp. In the lamp, therefore, the greatest

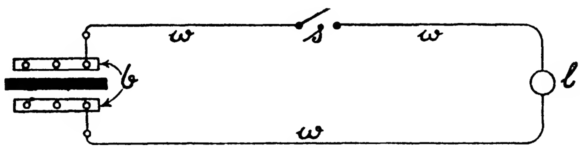


FIG. 136.

absorption of electrical energy will take place and the heating of the filament gives ocular proof of this.

The rate of development of heat in a wire is one thing, and the temperature to which it is raised is another.

If *a* and *b* in Fig. 137 were two circular wires of equal length and resistance, the same current would develop heat

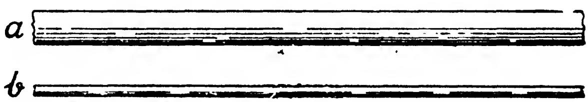


FIG. 137.

in both at the same rate. But if *a* be much thicker than *b*, due to their being of different resistivity, the temperature of *b* would be much higher, because the heat would be concentrated in less material, and because this small wire would have less surface for the dissipation of the heat.

The temperature to which a wire of a given size is raised by a given current depends upon the facilities which the wire has for getting rid of its heat. Supposing a wire were carrying a current sufficient to make it red-hot when enclosed in a box, its temperature would be less if it were in the open air, and less still if a current of air were blowing upon it, for in these cases the air would carry the heat away faster. The extremely thin filament of a metal lamp is enclosed in a vacuum to preserve it from premature breakage, the vacuum also preventing the heat being carried away quickly from the filament.

With each kind of insulating material there is a certain maximum temperature which must not be exceeded. The heat generated in a covered conductor has to pass through the insulating material before it can get to the air, and it warms or heats this material on its passage. As the resistance of insulators decreases when they are heated, this is one reason why too much current must not be sent through insulated wires. Another reason is that the insulating material, if of rubber or bitumen, softens if overheated. If bitumen cables are run too hot, the copper conductor decentralizes and gradually pushes away the insulation below it.

Paper insulation is less affected by heat than rubber or bitumen, hence conductors covered with paper may be worked at a higher current-density, and therefore at a higher temperature.

If a number of circular copper conductors of different sectional area were each carrying currents proportional to these areas, they would be working at the same current-densities, and the rate of generation of heat would be proportional to the areas. With the same current-density—

Wire.	Sectional area.	Currents.	Current-density.	Resistance.	C^2.	$C^2 \times R$.
a	1	1	1	1	1	1
b	2	2	1	$\frac{1}{2}$	4	2
c	3	3	1	$\frac{1}{3}$	9	3

But the temperature of a conductor depends on the rate at which heat is carried away as well as on the rate of its generation. And as the only way the heat can pass from a circular conductor is from its surface, the temperature of a current-carrying copper cable will depend not only upon its sectional area and on the current-density, but also on the area of its surface exposed to the cooling action of the air.

Now the surface of a circular conductor, neglecting the slight difference due to its being stranded or solid, is proportional to its circumference; and it is because circumferences are *not* directly proportional to sectional areas that temperatures are not the same with equal current densities in all sizes. Sectional areas vary at a greater rate than circumferences.

In Fig. 138 the circles represent cross-sectional areas of

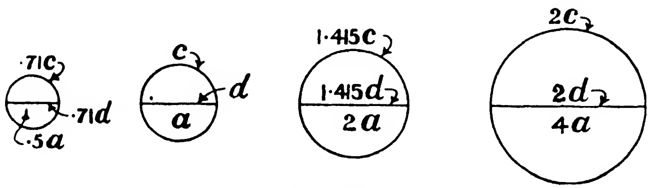


FIG. 138.

0·5, 1, 2 and 4 respectively; *d* being the unit diameter, *a* the unit area, and *c* the unit circumference. Then the proportions between circumference and area are shown by the figures. Cooling surfaces, or circumferences, are proportional to diameters, while sectional areas are proportional to squares of diameters. This means that if a certain size of conductor, worked at a given current-density, results in about the highest permissible temperature and the size of the conductor be increased, the current-density must be decreased. The same current-density in the larger conductor would cause the temperature-rise to become excessive.

Cables used in ordinary wiring work are exposed to the air or carried in casing or conduit. The smaller such a conductor is the more readily can it part with the heat generated in it by the current. Thus, to keep the current-density at a fixed value, say 1,000 amps. per sq. in., for all conductors, would result in over-heating large sizes and wasting copper in the small sizes. Considering heating alone, small conductors may safely carry much larger current densities than 1,000 amps. per sq. in., and therefore wiring tables have been prepared showing how the maximum densities and current-carrying capacity of wires vary for each size, with a fixed final temperature rise*.

This statement is illustrated by the following figures in which different sized conductors, varying in number and with diverse insulating materials, have their maximum permissible currents shown against them. The temperature rise for rubber insulation is 20° F., and for paper insulation is 50° F. The two smaller sizes, it will be seen, are allowed a current density of 4,000 amps. per sq. in., falling to something under 1,000 amps. per sq. in. for one sq. in. section.

Maximum currents with various sizes of conductors differently insulated—

Sectional area of conductor.	Vulcanized india-rubber.			Paper lead-sheathed.		
	Single cables.	Concentric cables.	Three-core cables.	Single cables.	Concentric cables.	Three-core cables.
sq. in.	amps.	amps.	amps.	amps.	amps.	amps.
0·001	4·1	3·5	—	4·1	3·5	—
0·003	12·0	10·3	—	12·0	10·3	—
0·01	31·0	26·6	23·2	42·0	36·0	31·0
0·03	53·0	46·0	40·0	87·0	76·0	66·0
0·1	118·0	100·0	83·0	191·0	162·0	134·0
0·3	240·0	188·0	—	385·0	302·0	258·0
1·0	595·0	—	—	932·0	—	—

Bus-bars are usually 3 in. × ⅛ in. If two bars are placed side by side close together, or separated by less than 1 in. distance, they will not carry twice the current of one bar with the same temperature rise. This is another case of cooling surface determining the proper current-density.

An insulated conductor gradually rises in temperature after current is switched on. At the beginning the temperature rises rapidly, but the higher the temperature the greater is the amount of heat dissipated per minute by

* See *Regulations for the Electrical Equipment of Buildings* of the Inst. Elect. Engrs. (Spon. 1s. 0d.)

conduction, convection and radiation. Consequently the curve representing the relation between temperature rise and duration of heating bends over gradually and eventually it becomes horizontal, thus showing that the heat lost = heat generated, with the result that the temperature does not increase any further.

130. INSULATION. The greater the pressure on a circuit, the better must be the insulation throughout. The pressure on electric bell circuits is only a few volts, and the cheapest wires are covered with cotton and afterwards steeped in melted paraffin wax to exclude moisture. Better wires for the same purpose have an inner covering of india-rubber. The fine wire for the magnet coils, forming part of bells, relays, and similar devices is covered with silk, cotton, or enamel. Sometimes bare wire is used, this being wound on with an insulating separator between each turn and between each layer.

The wires and cables used for interior lighting circuits are generally first covered with a layer of pure rubber, then with one of vulcanized rubber, over this a layer of tape, and lastly an outer braiding of cotton coated with some preservative varnish or compound. The copper wires are tinned to protect them from the action of the sulphur contained in the vulcanized rubber.

Large cables for street mains are often covered with specially treated paper, or with bitumen. Where the insulating material is not waterproof, it must be enclosed in a sheathing of lead to prevent the absorption of moisture.

Porcelain is largely used as an insulator, forming the body of lamp-holders, the bases of small switches, and the mounting for terminals and fuse-holders. Porcelain is a material produced from a mixture of ground-up flints, taken from the Channel shores of France; ball-clay and china-clay from Devon and Cornwall, which is granite in different stages of disintegration, and burned bone and other ingredients added for colouring purposes. The materials are ground-up in water forming a milky liquid called "slip." The water is then partially extracted by filter-presses, leaving a clay. This is then either moulded to shape or is powdered in a disintegrator, and the powder is compressed into the form of the finished article, which is then fired or subjected to a high temperature to drive off the water. This leaves a porous, hard material, in which it is known as the " biscuit " state.

By dipping the porcelain into a solution of lead and again firing it, the surface is covered with a glaze or outer surface which is impervious to moisture. The outer glassy surface of vitreous porcelain is easily cleaned and an excellent insulator.

Ebonite is easily worked and is useful for insulating collars and bushes, or for the slabs upon which terminals and parts of testing instruments are mounted, but it deteriorates with exposure to light; and, besides being brittle, will not retain its form or shape if subjected to heat.

In choosing an insulator for any given purpose, besides dielectric strength and resistance one has to consider such things as flexibility, mechanical strength, durability, effect of heat, influence of moisture, and the ease of manufacture into the required shape. Cost comes in as a deciding factor, except in those cases where insulation or some other property is so important that expense is of less moment.

131. INSULATION RESISTANCE. All conductors have to be insulated, otherwise the current would not be confined or restrained to their whole length. Diagrams often simply show the wires and the things they are connected to, ignoring altogether how these leads are insulated or supported. On paper there is no difficulty in keeping lines apart, but in practice there is ever more and more difficulty in finding room for all the cables which are coming into use for so many different purposes. Therefore wires are run side-by-side and must be covered with a continuous layer or tube of insulating material, which is to some extent a conductor, though a poor one.

So far as the insulation acts as a conductor, it does so at right angles to the copper circuit, as depicted in Fig.

139, where the leakage currents are at right angles to the current going through the circuit conductors + and –. Suppose the diagram represents a length of 10 yards. If in each yard there were a leakage of 1 micro-ampere, then, as the leakage paths are in parallel, the total leakage would be 10 micro-amperes, and the insulation resistance from + to conductors would be 200 volts/0·00001 amps. = 20,000,000 ohms, or 20 Ω. If we doubled the length, making it 20 yards, there would be double the leakage current, or 20 micro-amps., and the insulation resistance (shortly called the "insulation") would be reduced to half, or 10 Ω. Thus it follows that insulation decreases with length.

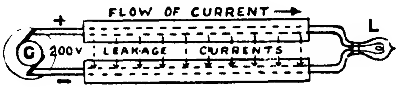


FIG. 139.

Since the leakage paths are at right-angles to the length of a cable, the area of insulating covering which conducts the leakage is proportional to the length of a cable, causing the insulation to be inversely proportional to the cable length.

EXAMPLE. 55 yds. of cable have a copper, or conductor resistance of 0·11 ohm, and an insulation resistance of 10,000 Ω. Find corresponding values for a mile length.

$$\text{Copper resistance} = \frac{1760}{55} \times 0{\cdot}11 = 3{\cdot}52 \text{ ohms}$$

$$\text{Insulation resistance} = 10{,}000 \times \frac{55}{1760} = 312{\cdot}5 \text{ megohms.}$$

None of the conducting parts of an installation, or network of circuits, can be perfectly insulated. Under the best possible conditions, there must always be some leakage of electricity, and the larger the installation the greater the leakage. This leakage is not a very definite sort of current, since it is made up of a multitude of infinitesimal currents passing through, or across the surface of, the insulation at numberless more or less weak points therein. When it passes across the surface it is called "surface leakage," which is often due to dirt deposited from the air on the exposed parts of an insulator, say at the ends of a cable.

Leakage takes place from the whole network of circuits in a system to earth ; the latter being represented by the tubing of interior wiring, sheathing of cables, the metal parts of lamp-holders, covers of switches, and the frames of motors. The better the insulation of a system, the less the leakage. The Electricity Commissioners' Regulations state that the leakage-current on any consumer's installation shall not exceed one ten-thousandth of the total current supplied thereto.

132. DIELECTRIC STRENGTH. One very important test for insulating materials determines what electrical pressure they can withstand before a spark forces its way through. This quality is called dielectric strength. The order of goodness of a few insulators is shown in the following brief list—

mica
ebonite
pure rubber
paraffined paper
micanite
vulcanized rubber
vitreous porcelain
ordinary glass
air

Insulating materials range themselves into quite different orders, for dielectric strength and resistance. Thus dry air has the greatest resistance and the least dielectric strength. There are many better insulators than mica and ebonite, considered from the point of view of resistance simply, but there are few better as regards dielectric strength. For this reason mica and micanite are largely used when thin layers of stiff and strong insulation are required. If a flexible insulator be required the only suitable things are the various grades of rubber. Where high temperatures are present asbestos is occasionally found satisfactory. An ingenious mode of utilizing the high insulating properties of porcelain is to make a number of small specially-shaped insulating pieces and thread them on the wire, a device termed " fish-spine insulation."

The insulation on cables and on magnet-windings, etc., before being considered satisfactory and passed for despatch to the buyer, are tested for dielectric strength by a "stressing" or "flash" test. Insulation may give a high resistance as measured by a low voltage, and yet break down electrically soon after it has been put into use.

It is consequently usual for the insulation to be subjected to a high alternating pressure, and if there is a weak spot the high pressure discovers and punctures it. It is cheaper in time and cost to detect and remedy such a fault rather than to have trouble when the insulation has been put

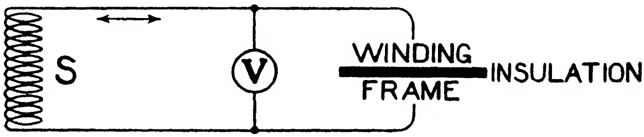


Fig. 140.

into service. The high pressure is raised gradually to its full value and then maintained constant for a few seconds to a minute or so. Fig. 140 gives a simple diagram of connections for a *flash test*, **S** being the secondary winding of a transformer. The voltmeter **V** indicates the gradual rise of pressure, and a break-down of insulation causes the sudden opening of an overload circuit-breaker connected usually on the primary circuit of the transformer.

It is because on an installation a weak point may exist which can only be found by the application of many volts that it is customary to require the insulation to be measured with twice the working pressure. On cable systems the most troublesome faults to deal with are those which give a high resistance when tested by a few cells, as used with instruments, but which break down when subjected to high pressures. It is occasionally necessary to employ several thousand volts to break down a fault which has sealed itself up temporarily but, unless dealt with, would be a source of risk to maintenance of supply.

133. EARTHING. The earth, or the globe, made up actually of earth and lots of other things, is so enormously large that no charge of electricity which can be given it makes any appreciable difference in its potential. Therefore the earth is taken as the base from which to measure potential; or we call its potential zero, and all other potentials are measured from that as a starting point.

The earth as a whole is relatively a good conductor simply because of its immense size. It does not follow that any particular mass of earth is a good conductor. In practice one learns that earth is a good conductor when circumstances would render it desirable it were not so; while if one wants to connect to earth, it is by no means easy to obtain such a connection of low resistance.

Electric lamp posts, and feeder-pillars on electric supply systems, have their bases buried in the soil, but it is not an uncommon thing to find they get "charged up" in the event of leakage to the "frame" or "post" unless they are connected to the general mass of earth by special wires.

When bell and other signals have to be given from a comparatively great distance, the saving of wiring by using an earth-return is considerable. An earth-return may also be utilized on simple telephone circuits, but as a general rule, telephones work better on a metallic circuit. It is, therefore, the practice nowadays not to include the earth in the circuit but to run a "lead" and a "return."

An earth connection for signalling circuits is best made by soldering the wire to a water-pipe, near to the point where the pipe rises from the ground; care being taken to ascertain that no junction or red-leaded joint comes between that connection and the ground.

For electric light and power circuits the earth connection must be thoroughly good, and the lead to it capable of carrying the maximum current which can flow at any time. This means that it should be at least one half of the cross-sectional area of the lead or return, and the metal should be copper. The resistance of lead and earth must be low enough to permit such a flow of current as will operate the fuse, or earth-leakage-trip of the circuit-breaker, protecting the system. Water pipes should not be used, but in small installations they are employed if they have metal-to-metal joints throughout. Gas pipes should *never* be included in the circuit.

An object is said to be " live " or " alive " when a difference of potential exists between it and the earth. A body is *earthed* when it is connected to the general mass of earth, in such a manner as to avoid danger ; the danger being the risk of the body becoming charged to such a pressure above earth that anyone standing on the earth and touching the body would receive a shock.

An earth-plate for small currents may consist of a sheet of copper 2 or 3 ft. square, buried well down in permanently damp earth and packed round in its hole with crushed coke. For large currents the plate is usually of cast iron, 3 or 4 ft. square, buried in the same manner, or a series of pipes are driven into the earth so as to expose a large surface. Even one earth plate is not relied on, but there are at least three, situated at points some distance apart and connected together by heavy bare copper tape, to which the earth-wires from machines, etc., about the works are joined by similar means.

Lamp-posts, the frames of street boxes, and so on, are best earthed by what has been called the " electrical octopus," i.e. a system of heavy copper tapes connected to the thing to be earthed and radiating outward for 3 or 4 ft. One such tape, of the section of lightning conductor strip, run out to each of the four cardinal points of the compass and thoroughly punned into the soil, will form a means of preventing a local rise of potential in the event of a leak, and thereby go a long way to guard against the risk of accidents through electric shock.

There are *three simple rules*, attention to which would remove most of the dangers attending the use of electricity. First, insulate and **guard** all live conductors ; either box them up or place them out of reach. Second, never leave dead conductors about so that they may become charged accidentally, but **isolate** them or block them off, capping ends of cables with insulating sheaths and plugging-up sockets with ebonite plugs. Third, **earth** every bit of metal not intended to be in the electric circuit, or which may have been so but is disconnected temporarily. A man standing in a bath, for instance, should not be able to get a shock by touching anything within reach, and to prevent accidents lamp-holders and switches should be placed out of reach, or properly earthed. In some power-houses all the metal frame of the building and everything else that could receive a charge is earthed.

It is on this principle that the rules for the use of electricity in factories require the frames of motors to be effectively earthed. Broadly, there should exist round every live conductor another conductor at earth-potential, interposed between the charged metal-work and the body of any person who may approach the place where the conductor is. Suppose work is going to be done on a main between two generating stations, or two feeding points. The correct procedure would be : Cut off supply at each end, thus isolating it ; then earth each end, when the work can be got on with.

A extra high tension cable is like a condenser and its dielectric absorbs a charge. Consequently it is not sufficient to discharge the cable by earthing it, and then removing the earth connection. The charge will soak out of the dielectric and raise the potential of the conductor, so that a dangerous shock may be received from it hours after it was disconnected from the supply.

QUESTIONS

1. What are the conditions necessary to set up an electromotive force, and to produce a current in a voltaic cell ?

2. A copper and a zinc plate immersed in dilute sulphuric acid are connected to a galvanometer, and it is noticed that the deflection gradually decreases ; why is this the case, and how can the action which causes the decrease be prevented ?

3. Describe fully the construction of the Leclanché cell, and add some hints as to how to maintain it in working order. What is the object of amalgamating the zinc in a galvanic battery, and why does it effect the required object ?

4. What is a "dry" battery, and how does it act? What special advantages does it possess, and what is its approximate electromotive force?

5. If you had a new form of primary battery submitted to you for trial, to what tests would you submit it in order to determine its utility?

6. Describe, with sketches, the construction and action of an ordinary vibrating electric bell, and the mode of connecting up bell, battery and push.

7. Why are electric bells apt to work badly when coupled in series? What is the white metal used for the tips of the contacts in electric bells? Why is silver sometimes used for this purpose?

8. Sketch the connections needful for bells between two places, *A* and *B*, so that a person at *B* can ring the bell at *A*, and that a person at *A* can ring the bell at *B*. One battery and one pair of wires only to be used; and only one bell to ring at a time.

9. Give a diagram with connections of a relay working an electric bell. Why cannot the use of a relay be dispensed with by using high battery power for working the circuit?

10. Describe, with sketches, a magneto-generator, such as is used for telephone calls.

11. Why is there a permanent steel magnet in the bells that are to be used with magneto-ringers? If electric bells are to be made to ring (by a magneto-ringer) through a line many miles in length, why must fine wire be used both in the coils of the ringer and in the coils of the electro-magnet in the bell?

12. Describe the manner in which a microphone acts in converting sound undulations into electrical vibrations. What are essential points in a telephone receiver in order that it may be as efficient as possible?

13. Why cannot additional loudness of speech be obtained in telephony by the use of higher battery power on any given transmitter?

14. What is meant by internal resistance in a battery cell? How can it be measured?

15. Distinguish between the electromotive force of a current generator and the potential difference between its terminals when working. A hot wire voltmeter may be used with accuracy for measuring the electromotive force of a storage battery; is the same instrument equally suitable for measuring the electromotive force of a battery of Leclanché cells?

16. The potential at the terminals of a battery falls from 10 to 6 volts if a resistance of 10 ohms is connected between its terminals. What is the resistance of the battery? *Ans.* $6\frac{2}{3}$ ohms.

17. A battery is sending a current through a wire. If this wire be gradually made shorter and shorter, describe what changes will take place (*a*) in the current, (*b*) in the p.d. at the terminals of the battery, and (*c*) in its e.m.f.

18. Explain what is meant by joining up battery cells in series and in parallel, and show how to determine the total e.m.f. and total resistance of the combination, the e.m.f. and resistance per cell of the battery being known.

19. What would be the total e.m.f. and the total resistance of six primary cells joined up three in series and two in parallel, the e.m.f. per cell being taken as one volt, and the resistance per cell as 5 ohms? *Ans.* 3 *v.* $7\frac{1}{2}$ ω.

20. Ten cells of 1 volt and 10 ohms each are used to send a current through an instrument of 200 ohms four miles away through a line having $12\frac{1}{2}$ ohms per mile. Find the current. *Ans.* $\frac{1}{35}$th ampere.

21. A trembler bell of 50 ohms resistance, which requires a current of 100 milliamperes to work it, is joined up on a circuit of 100 ohms resistance. How many cells, each having an e.m.f. of 1 volt and resistance of 5 ohms, would be required? *Ans.* 30 cells.

22. Three dry cells in series have a total e.m.f. of 4·3 volts. Each cell has an internal resistance of 0·3 ohm. They are connected to a lamp having a resistance of 7·7 ohms. State the p.d. at the terminals of the lamp. *Ans.* 3·85 volts.

23. Explain why it is useless to put a lot of cells in parallel if the line resistance is much greater than that of a single cell; and why it is useless to put a lot in series if the line resistance is much less than that of one cell.

24. Two dry cells each have an e.m.f. of 1·5 volt and an internal resistance of 0·3 ohm. How would you couple them up so as to give the greatest current through a wire having a resistance of 0·4 ohm and what would be the value of the current? *Ans.* In series, 3 amps.

25. A battery of 6 cells, each having an e.m.f. of 1·5 volts and res. of 1·2 ohms, arranged first in series and then in parallel, is used to send current through an external resistance of 0·5 ohm. Calculate the p.d. between the battery terminals in each case. *Ans.* 0·584 and 1·072 volts.

26. You have 15 cells each of 1 ohm res. and e.m.f. 1·09 volts. What is the maximum current you could get through a conductor of 1·67 ohms resistance? *Ans.* 1·63 amps.

27. How would you arrange a battery of 6 cells, each 1·4 volts and 2 ohms, to get maximum current through a wire of 3 ohms, and what would be the current? *Ans.* 0·7 amp.

28. Which would give the strongest current through a circuit of 30 ohms resistance: (*a*) 12 cells of a battery, all in series, or (*b*) 8 cells arranged 4 in series and 2 in parallel? The resistance of each cell is 10 ohms. *Ans.* Currents equal.

29. One hundred battery cells, each having an e.m.f. of 1 volt and int. res. of 5 ohms, have to be joined up to send the maximum current through an external resistance of 125 ohms. Illustrate by diagram how they should be connected, and prove the result.

30. If you have to work a number of circuits from a single battery, show by a numerical example that it is necessary that the battery have a low resistance in order that the currents going through any one line may not materially vary in strength when the other circuits are being worked.

31. A 100-volt lamp in series with a resistance is connected across 120-volt supply-mains. Explain why the light diminishes on

connecting a voltmeter across the lamp terminals to acertain if its p.d. is correct.

32. Show that if a large number of similar lamps, spaced out at equal distances between two mains, are required to give approximately the same light, it is necessary (*a*) that the lamps should be of relatively high resistance, and (*b*) that the mains should be of relatively low resistance.

33. An electromagnet wound with two equal wires, each having a resistance of 10 ohms, is connected to a battery of 20 volts electromotive force, and having an internal resistance of 10 ohms. Would the strength of the electromagnet be greater when the coils of the same are joined in series or in parallel ? *Ans.* C in each wire $\frac{2}{3}$ amp. in both cases.

34. Explain why an electromagnet with a total resistance of 50 ohms, connected direct to a battery of very low resistance, will be more powerfully magnetized if its two coils are joined up in parallel than would be the case if the coils are joined up in series. Also explain why the reverse is the case if the battery and electromagnet be in circuit with a resistance which is very high compared with the resistance of the electromagnet.

35. Two batteries, A and B, each of 1 volt electromotive force and of 5 and 10 ohms resistance respectively, have the + pole of A joined to the − pole of B, and the − pole of A joined to the + pole of B. What is the potential difference between the respective junctions ? *Ans.* Int. drop in $A = \frac{2}{3}$ v. and in $B = 1\frac{1}{3}$ v. $\therefore$ p.d. $= \frac{1}{3}$ v.

36. Two dynamos a and b have no-load e.m.f.'s of 520 and 515 volts respectively and full load p.d.'s. of 500 volts with 50 amperes. If they have straight line characteristics how will 75 amperes divide between them when they are run in parallel ? *Ans.* Int. res. of $a = 20/50 = 0{\cdot}4\omega$, and of $b = 15/50 = 0{\cdot}3\omega$. $\therefore$ $520 - (C_1 \times 0{\cdot}4) = 515\ [75 - C_1) \times 0{\cdot}3]$ which gives $C_1 = 39{\cdot}3$ amps, whence $C_2 = 35{\cdot}7$ amps. Proof is that $39{\cdot}3 \times 0{\cdot}4 = 15{\cdot}72$ volts, and $35{\cdot}7 \times 0{\cdot}3 = 10{\cdot}71$ volts, so that $520 - 15{\cdot}72 = 10{\cdot}71$, i.e. the p.d.'s are the same, 504·28 volts.

37. Two dynamos have respectively 252 and 248 volts on open circuit, and have 240 and 238 volts when each is giving 100 amperes. Assuming the e.m.f.'s. do not alter, and that they are joined together to supply a total of 150 amperes, how much current will each dynamo give ? *Ans.* 86·36 and 63·64 amps.

38. A cell of 1·5 volts and 5 ohms res. is connected to resistances of 100 ohms and $33\frac{1}{3}$ ohms respectively in parallel. How much current will pass through each resistance ? *Ans.* $12\frac{1}{2}$ and $37\frac{1}{2}$ milliamperes respectively.

39. Three resistances coupled in parallel receive current from a battery, having an open circuit e.m.f. of 6 volts and int. res. of 0·2 ohm. The resistances are 2, 3 and 6 ohms. What will be the pressure across the battery terminals ? *Ans.* 5 volts.

40. A primary battery is required to give a current of 1 ampere intermittently to actuate an apparatus which has a resistance of 7 ohms. A suitable kind of cell is made in two sizes, both giving the same e.m.f., but when giving 1 ampere the smaller size has a p.d.

of 0·7 volt while the larger size has a p.d. of 1·00 volt. If the cells cost 2s. and 3s. each respectively, which size would give the cheaper battery ? *Ans.* Smaller, £1 ; larger, 21s.

41. In what manner do (*a*) the conductor resistance and (*b*) the insulation resistance of a uniform electric light cable depend upon the length of the cable ?

42. What is meant by the "drop" in electric conductors ? How does the cross-section of a conductor and the current passing through it affect the drop ? How is the importance of a certain drop in a given case affected by the voltage of the circuit ?

43. If a conducting cable has a resistance of 0·2 of an ohm and a current of 500 amperes is passed through it, what will be the fall of volts along the cable ? *Ans.* 100 volts.

44. If a current of 20 amperes is flowing in a wire of which the resistance is 3·2 ohms per mile, state what will be the "drop" for each 110 yards of this conductor. *Ans.* 4 volts.

45. The resistance of 1 mile of a certain wire being 3·04 ohms, calculate the joint resistance of a quarter of a mile of 19 such wires laid parallel, not stranded, and calculate the fall in volts along half a mile of such cable when a current of 100 amperes is flowing along it. *Ans.* 0·04ω ; 8 volts.

46. If the resistance of 1 cu. in. of copper is 0·66 microhm, and the diameter of each of a pair of wires be 0·064 in., what length of circuit can be used so that the drop shall be 2 per cent, when the pressure between the wires at one end is 200 volts, and the current flowing through lamps connected between the wires at the other end is 2 amperes ? *Ans.* 135·4 yds.

47. The electrical installations of two detached buildings, one 200 and the other 700 yds. from the source of supply, require maximum currents of 150 and 50 amperes respectively. What cross-sectional areas of copper should be employed in the supply circuits to give "drops" of 5 and 7 volts respectively at full load ? *Ans.* 0·288 sq. in. ; 0·2376 sq. in.

48. A feeder, half a mile long, has to deliver 100 kilowatts at 440 volts. What cross-section must the conductors have so that the loss in the feeder may not exceed 5 per cent of the power delivered ? *Ans.* 0·4363 sq. in. The drop is 22 volts and current-density 520 amps. per sq. in.

49. A d.c. motor, taking 50 amps. at 500 volts, is supplied by a dynamo 400 yds. away. Res. of each conductor is 1·245 ohms per mile. Find the pressure at the dynamo terminals and the efficiency of transmission. *Ans.* 528·3 volts ; 94·64 per cent.

50. A cable is required to supply a 50 h.p. 250 volt motor, situated 100 yds. away from the distribution centre. Find the area of cable needed if the full-load drop must not exceed 4 per cent. Take ρ = 1·66 microhms per cm. cube, and motor efficiency = 0·85. *Ans.* 0·533 sq. cms. or 0·0824 sq. in. Current-density is 2,125 amps. per sq. in.

51. Explain what limits the current which a conductor may carry. Calculate the size of conductor, the voltage drop and power loss in the conductors supplying a 10 h.p. motor of 85 per cent efficiency with power at 220 volts, situated 440 yds. distance from

the generating station, when the permissible current-density is 1,380 amps. per sq. in. and $\rho = 0{\cdot}67$. *Ans.* 0·0289 sq. in.; 29·3 volts; 1,166 watts.

52. 600 h.p. at 600 volts are delivered at a place 2 miles distant from a generating station. Find the power of the generator required if the loss in transmission is 14 per cent of the power delivered. Also determine the cross-section of the cable. *Ans.* 510 kw.; 1·5 sq. in. Each amp. represents a h.p. $\therefore$ $C = 746$ amps. The drop is 14 per cent of $600 = 84$ volts, which for 2 miles circuit represents a current-density of about 500 amps. per sq. in.

53. How is the efficiency of electric transmission affected by the pressure between the conductors? What must be the cross-section of conductors required to deliver 400 kw.'s at 2,000 volts at a distance of 2 miles with an efficiency of 85 per cent? *Ans.* 0·09477 sq. in. The drop is 353 volts, which means a current-density of about 2,000 amps. per sq. in.

54. Explain fully why wires of small cross-section can be run at a higher current-density than wires of large cross-section. What are the usual minimum and maximum current densities in practice?

55. Three conductors, each of copper, of the same conductivity and each of the same length, namely, 1 mile, have cross-sectional areas respectively of 0·00322, 0·00503, and 0·00849 sq. in. If the ends of the conductors are connected to terminals between which a p.d. of 43 volts is maintained, what will be the current-density in each conductor, and will it be the same or different? *Ans.* 1,028 amps. per sq. in. The current-density will be the same in each conductor.

56. If currents are flowing in a network of conductors, explain the means by which the dissipation of energy in horse-power can be calculated. Explain fully what rule should, according to Lord Kelvin, determine the size of the conductors in any system employed for transmission.

57. Illustrate Lord Kelvin's law of economic proportion in cost of lines by an example of continuous-current power transmission; taking the case of a line for delivering 100 h.p. at a distance of 4 miles; maximum voltage 3,000 volts.

CHAPTER VI

THE MAGNETIC CIRCUIT

The elements of the subject are given in the author's *First Book of Electricity and Magnetism.*

134. MAGNETIC PROPERTIES. Iron and steel are the metals whose magnetic properties are of most practical value. When we say that a piece of iron or steel is magnetized, we mean that its already magnetized molecules have been so arranged in line as to give us useful magnetism.

Magnetism means the existence of lines of force. If these lines complete their path wholly through a magnetic medium, there is no *free magnetism* ; the latter existing only where the lines leave the magnetic body and pass through air.

Magnetic lines of force give rise to *lines of induction* in the iron, air, or other medium through which they pass.

135. REMANENCE. The free magnetism left in a bar of iron or steel after it has been removed from the influence of a current-carrying coil or other magnetizing agent, is spoken of as **remanence** or *residual magnetism* ; and the property in virtue of which this magnetism is retained is known as *retentiveness.* Thus the retentiveness of cast iron is greater than that of annealed iron, but less than that of hardened steel.

Theoretically, it is because of the supposed closeness with which the molecules of hardened steel are packed together, that it is enabled to retain its free magnetism ; and it is because of this also that steel is not so strongly magnetized as soft iron while within a coil carrying a current. The molecules of soft iron may be supposed to be able to move among themselves with comparative freedom ; so that when a bar is within an exciting coil, the majority of the molecules turn in line in obedience to the lines of force of the coil. When removed from the latter's influence, they turn once more so as to complete their magnetic circuits among themselves, and the bar then exhibits no free magnetism.

Retentiveness or *permanence* is the power of retaining magnetism after the magnetizing force is removed.

Remanence or *residual magnetism* is the magnetism retained after the magnetizing force is removed.

Free magnetism may be said to exist where magnetic lines have to pass through air in order to complete their circuits. Thus there is no free magnetism in a uniformly magnetized ring of iron. Although the molecular theory of magnetism is generally accepted, the usual way of accounting for the increased number of lines when a magnetizable body is placed in a magnetic field, is to imagine that it is in virtue of the superior *magnetic conductance* of the magnetizable body, as compared with that of air or other so-called non-magnetizable body.

Magnetic conductance is termed permeance, and specific magnetic conductance is called permeability, and is denoted by the Greek letter μ (mu).

136. MAGNETIC FIELD. The magnetic properties of a magnet affect the surrounding space, and that space is termed a *magnetic field.* The simplest way to detect the direction of this field is to bring within its influence a delicately-suspended magnetic needle. The position in which the needle sets itself at any point indicates the direction of the field at that point, the N pole of the needle pointing in the + direction along the lines. In order to ascertain the *strength of the field*, or the closeness with which the lines are packed together, we might find the force exerted on one pole of a very long thin magnet, whose length was so great that the other pole was practically beyond the influence of the field. Such a single pole, if free to move, would travel along the field ; the pull or push exerted on it depending on the intensity of the field.

137. MAGNETIC BODIES. The magnetic field, if in air, is traversed by *lines of force.* In iron the magnetic lines are termed lines of induction. It is necessary to draw a distinction between lines of force and *lines of induction.* When magnetic lines are set up, either in air or any other body, we must look upon them as *lines of induction* due to the " flow " of *lines of force* through the body. When a given number of lines of force pass through a body, the number of lines of induction set up will depend upon the permeability of the body. The **permeability of air is unity,** so that the lines of induction set up therein are equal in number to the lines of force. In bodies which have greater permeability than air, that is to say, which " conduct " magnetic lines better than air, the lines of induction will exceed in number the lines of force. On the other hand, in bodies which have less permeability than air, the lines of induction will be less in number than the lines of force.

Paramagnetic bodies (iron, steel, nickel, platinum and a few other rare metals) are those which " conduct " lines of force better than air. In other words, paramagnetic bodies are those whose permeability is greater than that of air. Most other bodies are *diamagnetic*, i.e. they have less permeability than air. The permeability of iron and steel is much greater than that of nickel and cobalt ; and enormously greater than that of manganese, etc. Thus it is that iron and steel are the only paramagnetic bodies of any practical use.

The permeability of diamagnetic bodies does not vary nearly so much as that of paramagnetic bodies. Thus, while good samples of iron or steel may have permeabilities reaching up to 2,000 or 3,000 as compared with air (= 1) ; the permeability of the most diamagnetic body, viz., bismuth, is very little less than that of air.

Paramagnetic bodies are sometimes called *magnetic bodies*, and air and other diamagnetic bodies *non-magnetic.* The difference between magnetic and so-called non-magnetic bodies is, however (like that between conductors and insulators), one of degree only. That is to say, they all allow magnetic lines to pass through them.

138. MAGNETIC SHUNTS. The magnetic circuit is not, in most cases, as clearly defined as the electric circuit through which electricity flows. For though we may confine electricity to any given path by surrounding that path with something which, practically speaking, will not allow electricity to flow through it, there is no such thing as a magnetic insulator, for all bodies conduct magnetic lines to an appreciable degree.

But though there is no body which will act as magnetic insulator, yet an instrument, such as a galvanometer, may be screened from external magnetic forces by enclosing it in a massive soft iron case. Similarly, a magnet placed in a thick, soft iron box would not affect a magnetic needle outside the box. The explanation is the thick case or box of soft iron affords such a good path for the neighbouring lines-of-force—be they inside or outside—that there is no inducement for them to pass right through. Such methods of *magnetic shielding* are analogous to short-circuiting the terminals of a battery by a thick conductor or shunting an instrument with a very low resistance shunt; there being then little inducement for electricity to flow by any other path than the short circuit or shunt.

In Fig. 141 is represented the effect which the insertion of the core of an armature has in deflecting the field of a field-magnet, which otherwise would pass straight across from pole to pole. One disadvantage of the old ring armature lay in the fact that the inside turns of the coils were not instrumental in generating e.m.f., for they did not cut any lines. This will be clear from an inspection of the figure, where it will be seen that no lines pass through the hollow part of the core. If they did they would cause counter or reverse e.m.f.'s to be induced in the inner turns **I**; and such would tend to neutralize the e.m.f.'s generated in the outer portions **C C** of the coils.

Magnetic lines have no ends, and may be looked upon as stretched elastic bands which are always endeavouring to shorten themselves, or shrink up. In diagrams, however, it is not always necessary to show their complete path, as it would generally take up too much room, even were it possible to say exactly where a magnetic field ended.

139. LINKED CIRCUITS. Electric and magnetic circuits, when the latter are due to the former, are always linked together, and are at right angles to one another, however irregular in shape they may be. Thus in Figs. 47 and 57, the magnetic circuit, which is wholly through air, encircles the electric circuit. In Fig. 59 one half of the magnetic circuit is of iron, and the other of air. In

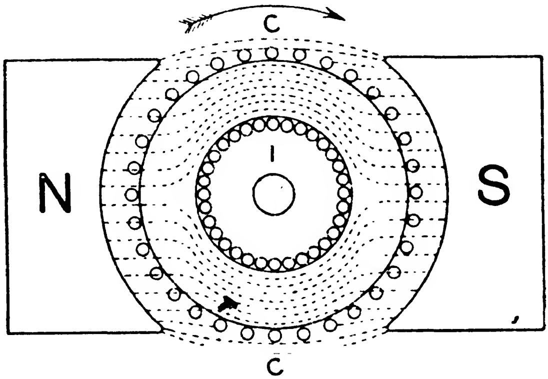


FIG. 141.—RING ARMATURE IN MAGNETIC FIELD.

Fig. 57 the circuit followed by the lines is through the coil and back again on all sides.

In Fig. 60, although we should get poles at the two ends of the spiral, as shown, the lines would not wholly follow the spiral iron path, but would leak across at the beginning and end of each separate turn, and there would consequently be weak poles there also. In Fig. 141 it will be noted that the magnetic field is in the plane of the paper and the electric circuit is at right angles to the page, the circles indicating a section of each of the wires wound on the core.

140. FLUX. There is similarity between the electric and magnetic circuits; and the relationship between the force producing a magnetic flux and the flux produced, may be treated in a similar way to that in which e.m.f. and current are dealt with in the electric circuit.

If we take a ring-shaped core of iron to represent the magnetic circuit, and wind round the iron core a coil of insulated wire and send a current through the coil thus formed, the iron of the ring will be magnetized, Fig. 142. We shall then have two closed circuits, the electric and the magnetic, and they will have their axes at right-angles to one another, like two links in a chain. An electric circuit must of necessity be closed to allow the current to flow. By *closed magnetic circuit* is meant one in which there is a complete path. In a magnetic circuit some of the lines will " flow " even when the circuit is " opened."

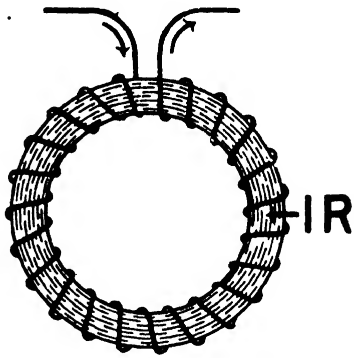


Fig. 142.—Magnetized Iron Ring.

The *magnetic excitation* produced by the current flowing through the turns of wire may be compared with the e.m.f. in the electric circuit, and is called **magnetomotive force ;** and the magnetic current, or total flow of magnetic lines, is termed *magnetic flux.* The magnetic resistance, or *reluctance,* of the iron ring would be found by dividing this magnetomotive force by the flux.

If we consider the electric circuit we have by Ohm's law, $C = E \div R$. In the magnetic circuit* we have—

$$\underset{\text{(Magnetic current)}}{\text{Flux } \mathsf{F}} = \frac{\text{Magnetomotive force}}{\underset{\text{(Magnetic resistance)}}{\text{Reluctance}}} = \frac{\mathsf{MMF}}{\mathsf{R}}$$

The magnetomotive force is proportional to the current

* Block letters are commonly used to indicate magnetic quantities, and in this chapter they are so employed.

and to the number of turns of wire on the coil, and gives rise to magnetic lines in the magnetic circuit, in this case composed of the iron ring. The product of the current in amperes, and the number of turns of wire, is called *ampere-turns.*

The **flux** is the total number of magnetic lines set up, and the reluctance is the magnetic resistance opposed to the setting up of these lines by the ring. Unfortunately, a simple law identical with Ohm's law, cannot be strictly applied in the case of the magnetic circuit. Resistance is a physically constant quantity, independent of the current flowing through a conductor, provided the latter be kept at a constant temperature, whereas the reluctance of an iron ring will vary with every change in the number of magnetic lines passing through it. $\mathsf{MMF} \div \mathsf{F}$ represents the magnetic resistance offered by the magnetic conductor, but it is not a constant quantity for different values of MMF and F. Therefore reluctance has not the same physical meaning for a magnetic circuit that resistance has for the electric circuit.

$R = E/C$ is true for any value of E or C, provided the circuit does not heat meanwhile. With a given resistance R, any increase of E or C will always be proportional to each other. If E be varied, C will vary in exactly the same ratio. R remaining constant. Thus, although $C = E/R$ in all electric circuits, the analogous magnetic formula $\mathsf{F} = \mathsf{M}/\mathsf{R}$ is only true for a particular value of F, inasmuch as the reluctance R depends upon F, whereas R is quite independent of C in the electric circuit.

The ability to conduct magnetic lines is the *permeance* of a material. Reluctance is the reciprocal of permeance; and *reluctivity* is the reciprocal of permeability.

141. MAGNETIC LEAKAGE. As regards electric current, bodies can be divided practically into conductors and non-conductors. But with the magnetic circuit, on the other hand, even so-called non-magnetic bodies such as air will carry the magnetic flux; so that a coil of wire with a current produces magnetic lines even if there be no iron in it. Thus it is that the magnetic circuit is not well defined. In a uniformly-wound iron ring most of it is through the iron but, especially if the exciting coil be all wound in one place, there is *magnetic leakage* through the air too (Fig. 143). If our electric circuits were all so leaky that we never knew the whole current produced by the e.m.f., and also never knew the resistance of the circuit (as would be the case, for example, if a hermetically

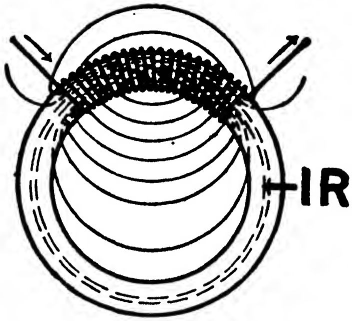


FIG. 143.—MAGNETIZED IRON RING.

The figure shows ten lines leaking through the air and only two passing through the iron, but these lines do not by any means represent the actual number and proportion in the two cases. As a matter of fact, the number of lines passing through the iron is far greater than the number of leakage lines. Thus in this, and in previous magnetic figures, the number of lines drawn only serve to give a very rough indication of the lines of the free magnetic field, which in reality pass through the air in all directions around the magnet, or current-carrying conductor, as the case may be.

sealed battery and a naked copper circuit were immersed in the sea), we should be unable to measure the current. We might define the current as the current in the copper only, but even that would be greater near the battery than in the more remote parts of the circuit. Again, in such a case, the current in the copper could not be found by dividing the e.m.f. by the resistance of the copper only; for Ohm's law could not very well be applied in a case where there was a leaking round of electricity by other paths, as through the sea-water.

The hermetically-sealed battery and naked copper circuit immersed in the sea form a very good analogue to the leaky magnetic circuit in Fig. 143 ; and it will now be understood that the simple magnetic-resistance method of dealing with the magnetic circuit is of little value when numerical calculations have to be made. It is useful, however, in giving students, who have mastered Ohm's law, a preliminary idea of the phenomena of magnetism.

In Fig. 142, the iron ring IR is entirely wound round with the coil of wire ; and the lines, which are primarily due to the current in the coil, will, practically speaking, keep wholly to the iron path, so that there will be no *magnetic leakage.* But if, as in Fig. 143, the current-carrying wire be all wound on one small portion of the iron ring, there will be considerable leakage of lines through the air, the amount of which will depend upon the ampere-turns of the coil, and on the size and cross-section of the iron ring.

The thicker the iron ring, the more inducement will there be for the lines to follow the iron path. The iron ring has much greater magnetic conductance, or permeance, than the surrounding air ; but its permeance will decrease, and its reluctance increase, as the number of lines passing through it increases.

142. FLUX DENSITY. In the case of a ring of wire, immersed in a conducting fluid, and an e.m.f. induced in a portion of the ring, we might reduce the doubt, which otherwise would exist, as to the e.m.f. by considering only the e.m.f. per unit length of that part with an induced e.m.f. in it. Instead of dealing with the total current we might consider the current per sq. in. cross-section of the conductor.

Now, it materially simplifies magnetic calculations to deal with the magneto motive force per centimetre of length instead of the whole m.m.f., and to base our working upon the magnetic flux per sq. cm. of cross-sectional area, instead of the total flux. Names have been given to these quantities, which renders it easier to talk about them.

If we divide the total m.m.f. by length in centimetres, we get the **magnetizing force,** i.e. the m.m.f. *per* centimetre. No name has been given to the similar quantity in the electric circuit, except by using words which define it, i.e. the "volts per centimetre." The magnetomotive force per unit length of a solenoid, or magnetizing coil (of any cross-section), is called the magnetizing force of that coil, and is denoted by the block letter **H**.

The number of lines of induction passing through unit cross-sectional area (square centimetre) of the material forming the magnetic circuit is generally called the *flux density*, and is denoted by the symbol, the block letter **B**.

$$\text{In symbols, } \mathbf{H} = \frac{\text{m.m.f.,}}{l} \text{ and } \mathbf{B} = \frac{\mathbf{F}}{A}$$

Other terms having the same meaning as flux-density which have been used by different writers are *induction*, or *magnetic induction*, or *internal magnetization*, or *intensity of induction*, or *permeation*, or *number of lines per unit cross-sectional area in the material*, or *lines of induction per square centimetre of cross-section*, and are all indicated by **B**.

143. MAGNETIC POTENTIAL. A more complete theory of the magnetic circuit, which is, unfortunately, somewhat difficult to understand at first, requires us to regard a current-carrying coil of wire as setting-up *magnetomotive force* which in turn creates a certain *fall of magnetic potential* along the axis of the coil. The setting-up of the lines is primarily due to the magnetomotive force, and the *magnetic potential-difference* is measured by the work that would be done by a unit pole, if such a thing could be got loose and allowed to move along the axis of the coil from one end to the other.

A *c.g.s. unit magnetic pole* is one that repels a similar unit pole, 1 centimetre distant, with a force of 1 dyne.

The *c.g.s. unit current* is that current which, if led near the unit pole through a bit of circuit 1 cm. long and bent into an arc of 1 cm. radius, with the unit pole at the centre, acts on the pole with a force of 1 dyne. If, instead of a bit of circuit, we have a complete turn, the force on the pole will then be 2π dynes. For if c.g.s. unit current exerts a force of 1 dyne when traversing a part of a circle equal in length to the radius (i.e. 1 cm.), as just stated, the same current will exert a force of 2π dynes if it makes one complete turn round the magnet pole, for the circumference of a circle is 2π times the length of its radius.

The intensity (or strength) of a magnetic field at any point is measured by the force it will exert on a unit magnetic pole ; and a *field of unit intensity* will act on a unit pole with unit force (one dyne). Now it is convenient to imagine that in a field of unit strength there is one magnetic line for every square centimetre unit of cross-sectional area ; so that a field of any strength n is one having n magnetic lines per square centimetre, n being the particular number in question. Magnetic lines calculated according to this method are called *c.g.s. lines*.

As a unit pole is one which acts on a similar pole with unit force when at unit distance from it, it follows, from what has just been said about unit field, that at unit distance from such a pole the field will be of unit strength. Now if we take a point to represent a unit pole, and suppose it surrounded by an imaginary sphere of unit radius, the surface of the sphere will at all parts be at unit distance from the pole, and the strength of the field will be unity everywhere on the surface of this sphere. The surface of a sphere $= 4\pi r^2$, where r is the radius ; and as unit magnetic field has one line for every square centimetre of area, and further, as the surface of a sphere of unit radius is 4π cms., it follows that there are 4π *lines emanating from a unit pole.*

It can be proved, that if a unit pole could be allowed to travel round any path linked with a c.g.s. unit current making one turn, i.e. with a unit current-turn, the work done would be 4π ergs. This would be true whether the interlinked path were air, or metal, or both ; and whatever the shape or size of the wire coil, provided it had one current-turn. It then follows after what was said at the beginning of the paragraph, that *the magnetomotive force* of (or the magnetic potential-difference between) the ends of a current-carrying coil is equal to 4 π times the current-turns.

As the c.g.s. unit of current is ten times the ampere, the magnetomotive force or magnetic potential-difference (in ergs per unit pole) is $0{\cdot}4\pi$ times the *ampere-turns* in the coil, i.e. 1·257 times the ampere-turns. Thus, denoting current by C, turns by N, and magnetomotive force by $\mathbf{M}$,

$$\mathbf{M} = 4\,\pi\,CN = 12{\cdot}57\,CN \text{ when } C \text{ is in c.g.s. units,}$$

$$\text{or } = 0{\cdot}4\,\pi\,CN = 1{\cdot}257\,CN \text{ when } C \text{ is in amperes.}$$

In practical work C is measured in amperes, and the second equation is used, and $1\frac{1}{4}$ is taken as approximately equal to 1·257. Thus the magnetomotive force is equal to $1\frac{1}{4}$ times the ampere-turns.

The idea of magnetic potential is difficult to grasp ; but it is analogous to electric potential, or pressure in hydraulics. The total pressure in a hydraulic circuit, for instance, can be found by calculating the work done when a unit volume of water goes round the whole circuit, arriving eventually at the starting position.

144. PERMEABILITY. In a hydraulic circuit in which water is flowing, there will be a gradual drop of pressure in the pipe, owing to the power absorbed in overcoming the friction therein ; and the fall of pressure (or the power absorbed) per foot of pipe can be estimated. If the circuit include a turbine, the fall of pressure through it, or the power absorbed in it, will be considerable.

In the electric circuit, the electric potential or pressure falls more or less gradually along the circuit owing to the power absorbed in forcing the current through the conductor ; and the fall of volts (or the power absorbed) in any portion can easily be found.

In the magnetic circuit we can also think of fall of potential. The imaginary unit pole, in travelling round the circuit, would do so much work per centimetre in one part, and so much per centimetre in another ; the amount being determined by the force acting on the pole, and being equal to the force multiplied by the distance traversed by the pole. The force which would act on a unit pole at any point is called the *magnetic force*, or *magnetizing force*, at that point ; and the magnetic force is spoken of whether there be a pole there to be acted on or not. The *magnetic force is thus equal to the rate per centimetre at which the magnetic potential falls.* Magnetic force is commonly denoted by **H**, and equals **M**/*l*.

As previously explained, any field of magnetic force may be considered as being filled with lines, the number of lines per square centimetre of cross-sectional area being the same as the number of dynes that would be exerted on a unit pole placed in the field. The *magnetizing force* **H** *at any part of the magnetic circuit, may therefore be practically defined as being equal to the number of lines per square centimetre of cross-sectional area in air at that part.* This follows from air being taken as having unit permeability, hence the flux density in air is equal to the figure representing the magnetizing force ; just as the number of amperes in a circuit of 1 ohm resistance is the same figure as the volts in that circuit.

In an electric circuit, imagine a centimetre cube so cut that the electricity flows in and out at opposite sides, but does not cross the other four sides at all. The current could then be found by dividing the difference-of-potential between the opposite faces of the cube by its resistance from face to face. Or it could be found by multiplying the p.d. by its conductance. It follows, therefore, that the current through the cube would be equal to the product of the fall-of-potential per centimetre, and the specific conductance of the copper.

The current per square centimetre of cross-section is the current density ; and the current density in a conductor may thus be found by multiplying the specific conductance of the material by the rate of the fall-of-potential (i.e. fall-of-potential per centimetre) at that point. Similarly.

in the magnetic circuit, the *flux-density* (or number of lines per □ centimetre of cross-sectional area) is equal to the rate of fall of magnetic potential (i.e. the magnetizing force) multiplied by the *specific magnetic conductance*, or permeability μ of the medium.

This quantity—specific magnetic conductance—is equal to the reciprocal of the specific magnetic resistance or *reluctivity* (**R**′); just as in the electric circuit specific

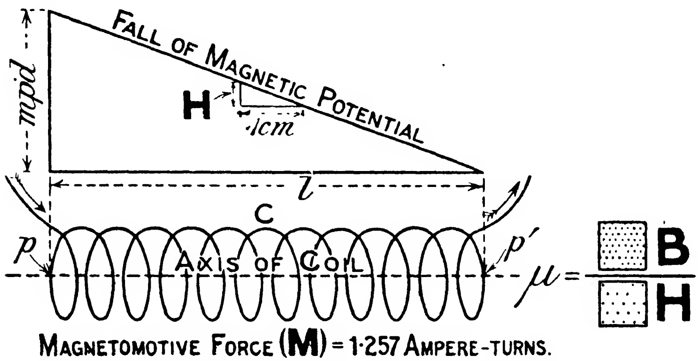


FIG. 144.—THE **M**, *mpd*, AND **H** OF A CURRENT-CARRYING COIL.

conductance (or conductivity) is the reciprocal of specific resistance (or resistivity).

$$\text{Thus, in the magnetic circuit } \mu = \frac{1}{\text{reluctivity}}$$

$$\text{just as in the electric circuit conductivity} = \frac{1}{\text{resistivity}}$$

145. MAGNETOMOTIVE FORCE. The *magnetic potential* at any point is measured by the work done on (or by) a unit pole in moving up from an infinite distance.

The *magnetic potential-difference* (*mpd*) between any two points in a magnetic circuit is measured by the work done on or by a unit pole in moving from one point to the other. With a current-carrying coil, the *mpd* between the ends of the coil is proportional to the magnetomotive force.

Fig. 144 illustrates roughly the connection between **M**, magnetic potential-difference (*mpd*), and **H** in a solenoid or current-carrying coil *C*. The magnetic field due to such a coil is roughly as indicated in Fig. 57, and the lines set up are primarily due to the magnetomotive force **M**. The magnetic circuit of a coreless solenoid is not well defined, but for practical purposes it is only necessary to consider that portion enclosed by the coil, i.e. from p to p' along its axis. Now the fall of magnetic potential along the coil may be indicated by the sloping line above, and the extent of the slope depends upon the magnetic potential-difference between p and p', this value being represented by the vertical line *mpd*. As already shown, *mpd* is proportional to **M**. **H** (the magnetizing force) is naturally greater the shorter the length l between the ends p and p' of the coil, but it is independent of its diameter. Thus **H** may be got by dividing **M** by l, which is the same as dividing *mpd* by l, the latter quotient giving the fall of magnetic potential per unit length, as indicated on the sloping line. The value of **H** obtained is that in the centre of the coil midway between its ends, as the field leaks away through the sides of the coil to a considerable extent. If an iron core is to be inserted, however, we may assume that **H** will be much more uniform from end to end of the coil, as the magnetic leakage will be greatly reduced. Now as **H** is equal to the number of lines of induction per unit of cross-sectional area in air, because air has unit permeability*; and further, as the increased number of lines per square centimetre **B** set up in an iron or steel core depends upon its permeability, we may express these relations graphically as shown at the right-hand end of the figure—

$$\text{Electric Circuit, } \frac{1}{\rho} = \frac{C/A}{E/l}, \text{ Since } \rho = \frac{E/l}{C/A}$$

$$\text{Magnetic Circuit, } \mu = \frac{\mathsf{F}/A}{\mathsf{M}/l}, \text{ Since } \frac{1}{\mu} = \frac{\mathsf{M}/l}{\mathsf{F}/A}$$

* Strictly speaking, the lines per unit area in air are lines of induction, and are the result of magnetic force (lines of force) acting on a medium of unit permeability. The flux per unit area has then the same value as the measure of **H**, but the quantities are of different kinds.

Where $\frac{1}{\rho}$ is the conductivity of the material in the electric circuit and μ is the permeability of the iron in the magnetic circuit.

In the magnetic equation, $\mu = B/H$, μ is not a constant quantity with any given piece of iron, but varies with every variation of H or B. Now as reluctivity is the reciprocal

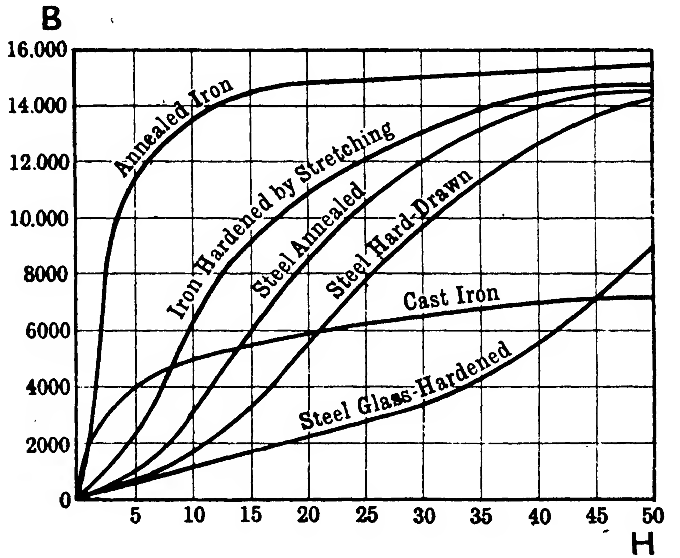


FIG. 145.—CURVES OF MAGNETIC INDUCTION.

of permeability, the former must vary with every change in the latter, though in an opposite sense. And if the reluctivity varies so also must the reluctance.

146. MAGNETIZATION CURVES. In Fig. 145 is shown a set of *curves of magnetization or induction* of different samples of iron and steel, in which the abscissæ represent the different values of the magnetizing or magnetic force (**H**), and the ordinates the resulting induction (**B**). Before being tested, each sample was perfectly devoid of free magnetism. Under a magnetizing force of 2·5, the annealed iron gave a value for **B** of about 8,000, the cast iron about 3,000, and the hard iron 1,000; while with the three samples of steel the induction was practically nil. When **H** = 5 we have the following approximate values—

Soft iron, 11,000.	Annealed steel, 900.
Cast iron, 4,000.	Hard steel, 800.
Hard iron, 2,150.	Glass-hard steel, 600.

It should be noticed that this small magnetizing force is sufficient to give nearly the maximum induction in soft iron, while there is only about one-fifth the induction in hard iron. This points to the importance of using well-annealed iron of the best quality whenever possible. It will also be seen that—though much less even than that in hard iron—the induction in annealed steel is more than that in the hard-drawn steel, and still more than that in the glass-hard steel. At these low values of **H**, however, there is little appreciable difference in the values of **B** for the different samples of steel. When **H** = 10, it will be seen that the curve for annealed iron is turning round in a horizontal direction. This denotes that we have nearly reached the practical limits of induction, or in other words, that the iron is becoming *saturated.* This being so, any further increase in the magnetizing force increases the induction very slightly indeed. The hard iron, however, does not begin to become saturated until about three times the magnetizing force has been applied, that is to say, when **H** = 30; but even at this point on its curve it only exhibits the same induction as would be given by soft iron with **H** as low as 9. Roughly speaking, this means that a magnet constructed of bad unannealed iron would require 3½ times as many ampere-turns, as would a similar sized magnet of good annealed iron, to magnetize each to a given induction.

When **H** = 50, it will be noticed that both the annealed steel and the hard steel have practically reached the saturation point, while the glass-hard steel curve is still rising sharply. From the position of this latter curve the student will understand how difficult it is to magnetize very hard steel, except with a great magnetizing force. Thus with **H** at 10 we see that the soft iron has practically reached its maximum value, while the steel is only just getting magnetized. The induction in glass-hard steel when **H** = 50 is equivalent to the induction in soft iron when **H** = 2·5: that is to say, hard steel would require about 20 times as many ampere-turns to magnetize to a given induction as soft iron.

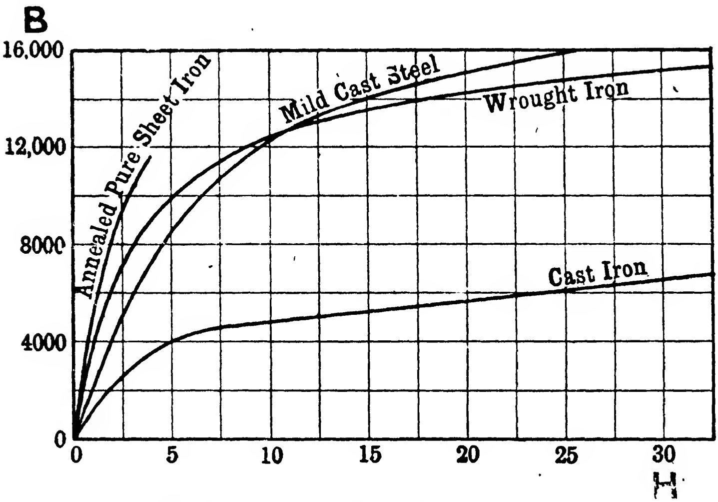


FIG. 146.—CURVES OF MAGNETIC INDUCTION.

Fig. 146 shows another set of curves. If the wrought and cast iron curves be compared with those in Fig. 145, they will be seen to have the same general shapes, and to traverse very nearly the same values of **H** and **B**. Any differences that are observed are due to differences in the quality of the specimens tested.

147. IRON AND STEEL. *Cast Iron* is obtained by melting iron ore with carbon; and carbon and various other impurities are retained.

Wrought Iron is cast iron which has been repeatedly heated, rolled, and puddled until most of the impurities have been burnt or squeezed out. Hence wrought iron is one of the purest forms of iron. After the above process it may be *hard-rolled*, and after this again it may be *annealed*. The latter process consists in heating the iron to bright redness, and then allowing it to cool very gradually in a bed of charcoal or some other material, to prevent its surface being "chilled" by contact with the air. Annealed iron of good quality is often referred to as *soft iron*.

Mild Steel is obtained by melting cast iron of special quality and then blowing air through it. It is easily rolled, and may also be cast. Although it contains more carbon than wrought iron, it has very similar magnetic qualities. On account of this, and also because it possesses greater tensile strength, it is often used for the frames and other parts of electrical machinery.

Sheet Iron and Steel. Both wrought iron and mild steel can be formed into thin sheets by repeated heatings and drawings. From such sheets, after they have been annealed, the thin core-plates for armatures, transformers, etc., are punched.

Cast Steel is mild steel with foreign bodies (such as carbon, nickel, tungsten, etc.) purposely introduced. The best brands of cast steel for making engineer's tools are made with special care in crucibles, and are known as *crucible cast steel* or *tool steel.*

Cast steel possesses the valuable property of *hardening* when heated to bright redness and then plunged suddenly into oil or water. In this state the steel is said to be *glass-hard,* this name indicating that the edges will scratch or cut glass. Glass-hardened steel has less permeance than any other kind. On the other hand, it has the greatest retentiveness. For this reason, permanent magnets are made of it.

In consequence of the brittleness of glass-hard steel, tools, knives and other implements (which are first fashioned in the unhardened steel, and are then hardened), have to be *tempered.* The tempering process consists in re-heating the hardened steel very slightly and then suddenly cooling it again; and its effect is to reduce slightly both the brittleness and the hardness of the metal. Cast steel—before it has been hardened and tempered—is often referred to as *soft steel.*

148. MAGNETIC QUALITIES. The permeability of annealed iron, unless very strongly magnetized, is much greater than that of any other body. It is therefore generally used as much as possible to constitute the magnetic circuit.

The value of μ varies with different samples; and with any particular piece of iron or steel, *first increases and then decreases* as the magnetizing force H increases. The induction B in a piece of iron is due to the alignment of its magnetized molecules; and as the magnetizing force is increased, more and more molecules are set in line, until there remain comparatively few to be acted upon. In this state we have what is known as the *saturation* of the material. Consequently, the induction B cannot go on increasing as the magnetizing force H is increased, and it follows that the permeability μ, after a certain point, must get less and less as the magnetizing force becomes greater. The permeability of any particular sample is therefore not a constant quantity, but diminishes as the metal becomes saturated. The permeability of air is taken as unity, so that in air $\mathsf{B} = \mathsf{H}$.

$$\text{As } \mu = \frac{\mathsf{B}}{\mathsf{H}}, \quad \therefore \mathsf{B} = \mu \mathsf{H}$$

Referring to the curve for soft iron in Fig. 145, when B is 12,000, the value of H corresponding with this = 6·5. Thus at these values the permeability μ

$$= \frac{\mathsf{B}}{\mathsf{H}} = \frac{12000}{6 \cdot 5} = 1{,}846$$

When B is 15,000 and $\mathsf{H} = 25$, the permeability = 15000/25 = 600. Thus in the second case the permeability has dropped to about one-third.

Owing to the gradual decrease in the permeability, there are limits to the useful induction. These limits depend upon the uses to which the magnetized iron is put. For dynamo field-magnets the practical limits of **B** are somewhat as follows—

Wrought iron.	About	16,000	lines per	□ cm.
	or	104,000	,, ,,	□ inch.
Cast iron.	About	6,000	,, ,,	□ cm.
	or	39,000	,, ,,	□ inch.

149. MEASUREMENT OF H. To obtain the values from which curves of induction are drawn, it is necessary to measure those quantities which can be observed by the use of ordinary instruments. The simplest method of arranging for this is to wind a coil of insulated wire round the rod of iron to be tested, and then connect the coil to a battery through an adjustable resistance, an ammeter, and a switch. The number of turns n of the coil, its length in centimetres l, and the direct current in amperes C being known, the magnetizing force **H** at the centre of the coil will be—

$$\mathbf{H} = \frac{\mathbf{M}}{l} = \frac{4\pi n}{l} \times \frac{C}{10}$$

the current being divided by 10 to bring it to c.g.s. units.

$$\text{Now as } \frac{4\pi}{10} = 0{\cdot}4 \times 3{\cdot}1416 = 1{\cdot}257$$

the above may be simply written, omitting the final figure—

$$\mathbf{H} = \frac{1{\cdot}25\,C\,n}{l} = \frac{1\tfrac{1}{4}\text{ ampere-turns}}{\text{length}}$$

This is only approximately true, however, except when the length l of the coil is at least 10 or 12 times its diameter. **H** represents the number of lines per square centimetre of cross-section of the coil, away from its ends, if air alone be the medium through which the magnetic lines pass. Thus the total number of lines will be found by multiplying **H** by the cross-sectional area **A** in square centimetres.

Ex. Calculate the total magnetic field at the centre of a long bobbin of wire, consisting of 250 turns wound as a helix 50 cms. long and 4 cms. in dia., traversed by a current of 10 amperes.

$$\mathsf{H} = \frac{1{\cdot}257 \times 10 \times 250}{50} = 63 \text{ lines per sq. cm.}$$

The flux (F) or total flow of lines in air will be—

$$\mathsf{F} = \mathsf{H} \times A$$

where A is the cross-section area in sq. cms.

$$A = \pi r^2 = 3{\cdot}1416 \times 4 = 12{\cdot}5664 \text{ sq. cms.}$$

$$\therefore \; \mathsf{F} = 63 \times 12{\cdot}5664 = 790 \text{ lines embraced by centre of solenoid.}$$

If iron were present instead of air, the number of lines would be very greatly increased.

If H be as above, and we insert an iron core whose permeability $\mu = 100$ for that value of H, then the lines of induction per square centimetre B would be equal to the permeability multiplied by the magnetic force, or—

$$\mathsf{B} = \mathsf{H}\,\mu = 63 \times 100 = 6300 \text{ lines.}$$

The total flux F in the iron would then be—

$$\mathsf{F} = \mathsf{B} \times A = 6300 \times 12{\cdot}566 = 79000 \text{ lines,}$$

or 100 times that through air alone.

150. MEASUREMENT OF B. If H and either B or μ be known, the other quantity is readily got. As a rule, however, B and μ have to be found by experiment.

There are various methods by which B can be determined. Some of these can only be used with bars which have free poles. One depends upon the relationship between B and the magnetic moment M' and intensity of magnetization I of a magnet; the two latter quantities being obtainable by calculation based on the deflections of a magnetic needle.

The *moment of a magnet* M' is the strength of one pole $\times$ the distance between the poles. Thus the *moment* of the electro-magnet formed by the piece of iron or steel under test and its magnetizing coil, is equal to the strength of either pole m of the magnet multiplied by the straight distance l between the poles, or $\mathsf{M}' = ml$.

The *magnetic moment* of a magnet is a measure of its tendency to turn when placed at right angles with the lines of any magnetic field.

M′ is readily compared with the *horizontal component of the earth's magnetic force H*, which varies at different parts of the earth. In other words, H is the force with which the earth's magnetism acts on a horizontally-suspended magnetic needle; and its value, which may be obtained from tables, is about 0·18 dynes in London.

An easy method of comparing **M′** with H is as follows. A magnetic needle, set in the earth's field, is deflected by the test-piece of iron in the coil; the latter being placed with the line joining its poles at right angles to the magnetic meridian. Then if d be the distance between the centre of the needle and either end of the test-piece, and θ the angle through which the needle turns from its position of rest: $\mathbf{M}' = d^3 H \tan \theta$.

Tangent values of angles are given in the table at the end of Volume II.

151. MAGNETIC MOMENT. The arrangements for this experiment are shown in Fig. 147, where $N\ S$ is a *deflection magnetometer,* i.e. a small and delicately-suspended magnetic needle provided with a long light pointer p, by means of which the amount of its deflection may be accurately noted. TP is the test-piece of length l, put into the coil of n turns. B is a battery, R an adjustable resistance, G a galvanometer, and K a key. TP must be placed at right angles with the needle's position of rest, and it must not be too close to the needle. This is called the " broadside-on " position.

The *intensity of magnetization* **I** of a magnet or iron bar is found by dividing its magnetic moment **M′** by the volume V of the iron.

$$V = \text{the length} \times \text{breadth} \times \text{thickness}$$
$$= \quad ,, \quad ,, \quad l \times \text{sectional area } A.$$

$$\text{Then} \quad \mathbf{I} = \frac{\mathbf{M}'}{V} = \frac{m \times l}{l \times A} = \frac{m}{A}$$

In other words, **I** is equal to the moment per unit volume, or to the pole-strength per square centimetre. The volume V can be ascertained by simple calculation from measurements with an accurate rule and calipers; and having found **M′** by means of the magnetometer, **I** is at once obtainable.

If **H** be calculated from the current, the length of the

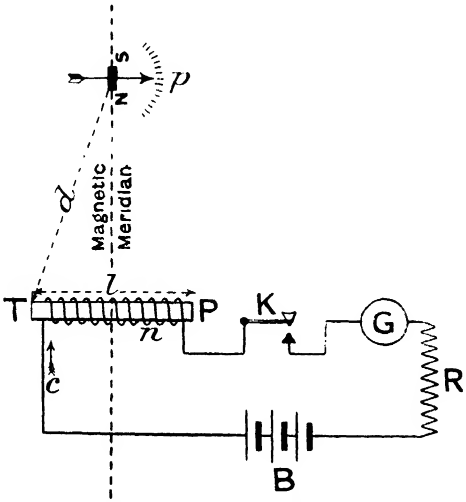


FIG. 147.—MEASUREMENT OF MAGNETIC MOMENT.

coil, and the number of its turns; **B** may be found from the following equation—

$$\mathbf{B} = 4\pi\mathbf{I} + \mathbf{H}$$

From this* the permeability could be found, since $\mu = \mathbf{B}/\mathbf{H}$.

152. CALCULATION OF μ. The flux-density **B** can be calculated as follows. If we know the current in the coil C, its number of turns n, the length l, the distance d between the end of the test-piece TP and the centre

* **H** is usually so small compared with $4\pi\mathbf{I}$ that it can generally be neglected.

of the needle, the angle of deflection of needle θ, and the volume of the test-piece V; then—

$$\mathbf{B} = \frac{4\,\pi\,d^3\,H \tan\theta}{V} + \mathbf{H}, \text{ or approximately } = K \times \tan\theta,$$

where $K = \dfrac{4\,\pi\,d^3\,H}{V}$. And $\mathbf{H} = k \times C$, where $k = \dfrac{1{\cdot}25n}{l}$

Then μ for each value of **B** and **H** = **B**/**H**.

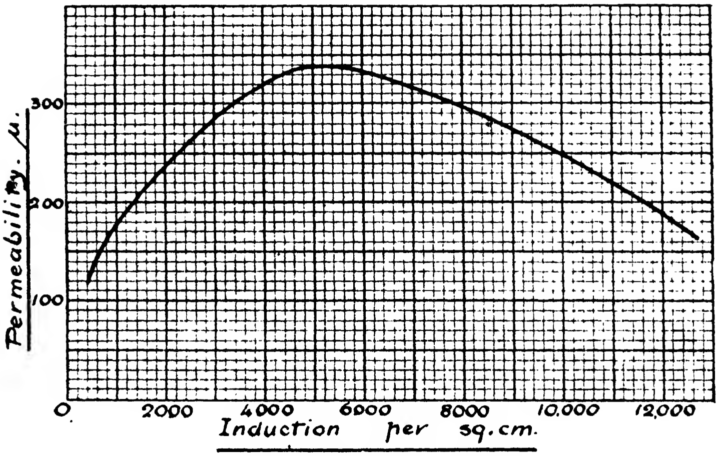


FIG. 148.—PERMEABILITY CURVE.

EXAMPLE. A piece of wrought iron 20 cms. long by 0·8564 sq. cms. in area was placed within a coil of 157 turns. The length of the coil was 23·7 cms., and it could carry up to 10 amps. At a distance of 29·53 cms., a deflection magnetometer was placed, the coil lying at right angles to the magnetic meridian (i.e. in the broadside-on position). Currents varying from ·6 to 9·6 amps. were passed through the coil, the deflections of the magnetometer needle being noted. The arrangement of apparatus was as described in the previous §. **H** was found to be 8·33 for every ampere passed through the coil.

The results obtained are plotted on the permeability curve shown in Fig. 148. The values of μ, calculated from the experimental observations, were derived from the formulae already explained. The values of μ were plotted as ordinates, and the corresponding values of **B** as abscissae. The ordinates were obtained by dividing the different values of **B** by the corresponding values of **H**.

From this curve a good idea can be obtained of what is meant by *saturation*. At about 5,000 lines of induction per square centimetre **B**, the iron reached its highest value of μ; and beyond this value its permeability gradually decreased, the curve bending downwards to the base line.

153. SUSCEPTIBILITY. Another quantity concerning any magnetic material is its *susceptibility* (κ)* to magnetization, this quantity bearing the same relationship to **I** that μ does to **B**.

Thus $B = \mu H$ and $I = \kappa H$

$$\text{Consequently } \mu = \frac{B}{H} \quad \text{and } \kappa = \frac{I}{H}$$

Susceptibility relates to the *intensity of magnetization* produced in a body by a magnetizing force, whereas permeability is a measure of the body's power of *conducting* lines. A full explanation of the former term involves the consideration of what is sometimes termed *surface magnetism*, an idea which we wish to avoid if possible. Of the two quantities, permeability and susceptibility, the former is the more useful to the engineer, so that we need not devote any further consideration to the latter.

154. DRYSDALE'S PERMEAMETER. Instruments for measuring permeability are called *permeameters*. Many such have been devised, but most suffer from the drawback that tests have to be made on specially-prepared samples. With Drysdale's permeameter, however, the test is made upon the actual casting or forging.

The body of iron to be tested has a hole drilled in it by a special drill which leaves a pin up the centre of the hole; and a soft-iron test plug carrying two small coils of fine wire is then inserted in the hole. This plug is connected up to a test box and the test made.

* κ = Greek letter, *kappa*.

A section of the plug is given in Fig. 149, the hole made to receive it being about $\frac{5}{8}$ in. deep and $\frac{3}{8}$ in. diameter. The plug is thus shown nearly its actual size.

M is the material under test, such as the actual casting or forging which will eventually form part of the finished machine. *P* is the pin forming part of *M*, and left in the centre of the hole by the hollow drill. The plug, which carries two separate coils, *MC* (magnetizing coil) and *SC* (search coil), is split down the centre (as at *S*), so that when wedged into the hole it grips the pin *P* closely. The wires from the two coils pass up through the holes *H*, and are connected by flexible leads to the testing apparatus. The figure also shows the general form of the magnetic field set up when current is sent through *MC*.

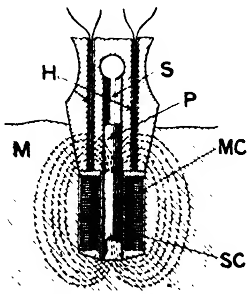


FIG. 149.—TEST PLUG.

The test box, Figs. 150-2, contains a *ballistic galvanometer BG*, of the moving-coil type, a 2-cell dry battery *B′*, two reversing switches (*BRS* and *GRS*) for battery and galvanometer respectively, a rheostat *R*, a two-way galvanometer switch *TG*, a galvanometer *damping key K*, a compensating coil *CC*, a resistance *R′* in circuit with the search coil, and another *R″* in the battery circuit. The sensitiveness of the galvanometer is adjusted (by the makers) by means of these resistances, and they need not be considered further. *SS* are the search-coil terminals, *MM* those of the magnetizing coil, and *BB* battery terminals to which an outside battery (of 3 volts) may, if desired, be connected in place of the dry cells.

The battery and galvanometer reversing switches have each three positions: *BB* (= *break*), *DD* (= *direct*), and *RR* (= *reverse*), as indicated in Fig. 151.

The directions for making the tests are as follows, it being presumed that the test-piece is already drilled and the plug inserted therein, and also connected up to the instrument.

(*a*) Check the battery current by setting *BRS* and *GRS* to *direct* and *TG* to *batt*. The galvanometer pointer should then swing to the red mark on its scale. If it does not,

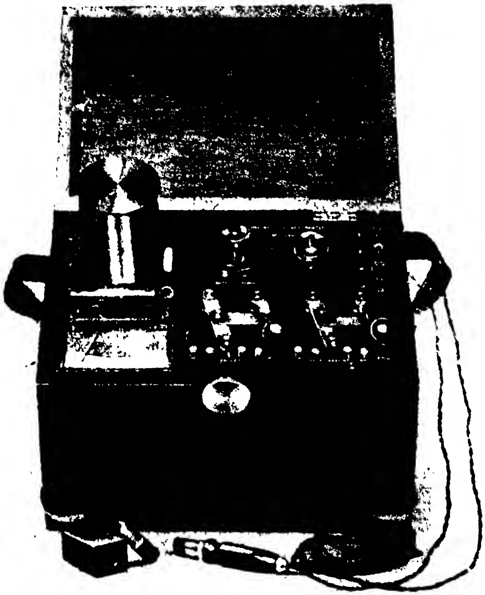


Fig. 150.—Drysdale's Permeameter.

the current must be adjusted by means of the rheostat *R*. The calibration of the galvanometer is such that a deflection to the red mark ensures a magnetizing force (**H**) of 50 in *MC*.

As the galvanometer is *ballistic* on action, that is to say, as it has a comparatively heavy moving part, the reading is taken of the full extent of the *first* swing of the pointer.

(*b* Set *TG* to *perm.* and allow the galvanometer to come exactly to zero, this being hastened by depressing *K* at intervals. Now move *BRS* quickly from *direct* to *reverse*. The reading of the first swing of the galvanometer as read

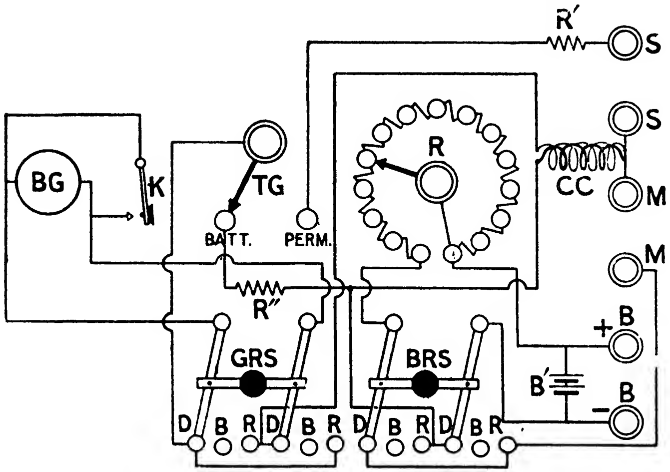


FIG. 151.—ACTUAL CONNECTIONS OF DRYSDALE'S PERMEAMETER.

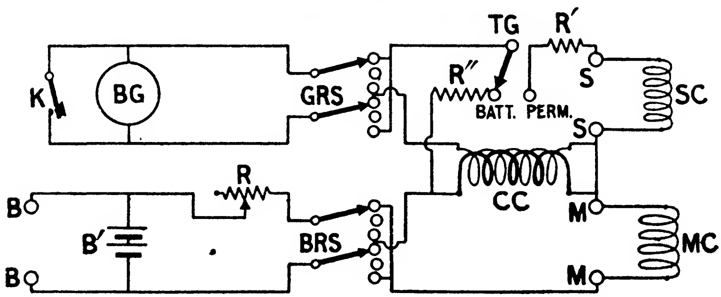


FIG. 152.—SIMPLIFIED DIAGRAM OF CONNECTIONS.

on the permeability scale will give the value for the test-piece. At the same time the reading on the **B** scale will give the value of the induction.

Without the use of the damping key the galvanometer would take some time to come to rest at zero. The effect of closing the key is to short-circuit *G*, and the currents induced in the moving coil as it swings in the field of the permanent magnet of the galvanometer will then help to bring the moving part to rest.

(*c*) To check the result just obtained, bring the galvanometer to rest by means of *K*, and set *GRS* to *reverse*. Then change *BRS* quickly from *reverse* to *direct*. The deflection obtained should be equal to the previous one. If it is not, the mean of the two may be taken as the correct value for μ and **B**.

We know from (*a*) that the magnetizing force (or **H**) of *MC* is 50; and the winding of this and of *SC*, and the markings of the two galvanometer scales (which are fixed side by side), are such that correct values of μ and **B** are indicated for this value of **H**. The movement of *BRS* to *direct* or *reverse* sends the current in opposite directions round *MC*; while *GRS* reverses the connection of *SC* to the galvanometer when *TG* is on the *perm.* contact.

In (*b*) the current is already flowing one way round the plug, but there is no deflection on the galvanometer as the field is steady. On changing over the battery connection the field is reversed, the lines first collapsing and then spreading out in the reverse direction. This double action results in the induction of an e.m.f. in *SC* proportional to the number of lines of induction in the specimen, i.e. proportional to the permeability thereof. The galvanometer swing will consequently denote this value.

In (*c*) the previous result is checked by starting with the magnetizing field *MC* in the reverse direction, but this second test is not absolutely necessary. It serves, however, to show if there is any appreciable residual magnetism in the specimen.

The compensating coil *CC*, which is really a small induction coil, serves the purpose of compensating for stray magnetic lines due to the test-piece; but we may neglect the presence of the coil, as it could be dispensed with in ordinary tests. The diagrams given should be compared, and copied out by the student, as similar sets of connections occur frequently in later work.

When a sample of iron to be tested is in the form of a ring, this is wound with two coils, one as a magnetizing coil and the other as a search coil, and the test is taken in a similar manner to that described above.

155. THE MAGNETIC CIRCUIT. The simplest form of magnetic circuit is that shown in Fig. 142, namely, a circular iron ring of uniform sectional area A, and evenly wound with an exciting coil of n turns. If B be the flux-density in the iron, the flux F through that circuit is given by $\mathsf{B} \times A$.

The flux F is directly proportional to the magnetomotive force M of the magnetizing coil, and inversely proportional to the reluctance R of the magnetic circuit.

$$\mathsf{F} = \frac{\mathsf{M}}{\mathsf{R}} = \mathsf{B} \times A$$

This relationship is really a sort of Ohm's law for the magnetic circuit, where F, M and R correspond to C, e.m.f. and resistance of the electric circuit.

The magnetomotive force due to a direct current of C amperes flowing round n turns is given by $\mathsf{M} = 1{\cdot}25 \times C \times n$.

Permeance in the magnetic circuit is analogous to conductance in the electric circuit. The reluctance and permeance of any magnetic material vary with every change in the flux passing through it ; but the reluctance of the material, at any stated value of the proposed flux, gives the corresponding value of the permeance—

$$\text{Permeance} = \frac{1}{\text{reluctance}}$$

The permeance of any portion of a magnetic circuit is directly proportional to its sectional area A and its permeability μ, and inversely proportional to the length l of that portion. Permeability is the reciprocal of reluctivity, just as conductivity is the reciprocal of resistivity.

If the permeance be given, the ampere-turns Cn required to produce a certain m.m.f. to force a stated number of lines through a magnetic circuit of known dimensions can be found quite readily. As magnetic circuits are not always uniform in quality or in section, it is simpler to find the ampere-turns required per unit of length, instead of the total ampere-turns. Also, it is better to deal with the flux per square centimetre of cross-section, instead of the total flux, and with permeability instead of permeance.

Ex. (*a*) A ring, of 15 in. in mean diameter, is made of round soft iron 1·5 in. dia. When the permeability is 900, the flux-density is 13,500 lines per sq. cm. *Find ampere-turns*, and *total flux.*

Mean length of magnetic circuit = 3·1416 × 15 × 2·54 = 119·7 cms.

$$\mathsf{H} = \frac{1{\cdot}25 \times Cn}{119{\cdot}7} = \frac{\mathsf{B}}{\mu} = \frac{13500}{900} = 15$$

$$Cn = \frac{119{\cdot}7 \times 15}{1{\cdot}25} = 1438 \text{ ampere-turns.}$$

Sectional area of iron is, $0{\cdot}7854 \times 1{\cdot}5^2 \times 2{\cdot}54^2 = 11{\cdot}4$ sq. cms.

Flux = $\mathsf{B}A = 13500 \times 11{\cdot}4 = 153{,}910$ lines.

In the electric circuit—

$$\text{Resistance} = \frac{l}{A} \times \rho = \frac{l}{A \times \text{conductivity}}$$

and, similarly, in the magnetic circuit—

$$\text{Reluctance} = \frac{l}{A} \times \text{reluctivity} = \frac{l}{A \times \mu}$$

Substituting the values, we get—

$$\mathsf{F} = \mathsf{B} \times A = \frac{1{\cdot}25\, Cn}{\dfrac{l}{A\mu}} = \frac{1{\cdot}25\, Cn\, A\mu}{l}$$

$$\text{and } \frac{Cn}{l} = \frac{\mathsf{B}A}{1{\cdot}25\, A\mu} = 0{\cdot}8\ \frac{\mathsf{B}}{\mu}$$

In words, this means that the ampere-turns per unit of length are equal to 0·8 times the flux density ÷

permeability. For a given flux density **B**, the worse the permeability, the greater the number of ampere-turns which must be provided in the exciting coil, or in the field-magnet windings of a dynamo. Thus, the number of ampere-turns required per unit of length of the magnetic circuit depends only upon the flux-density and the permeability.

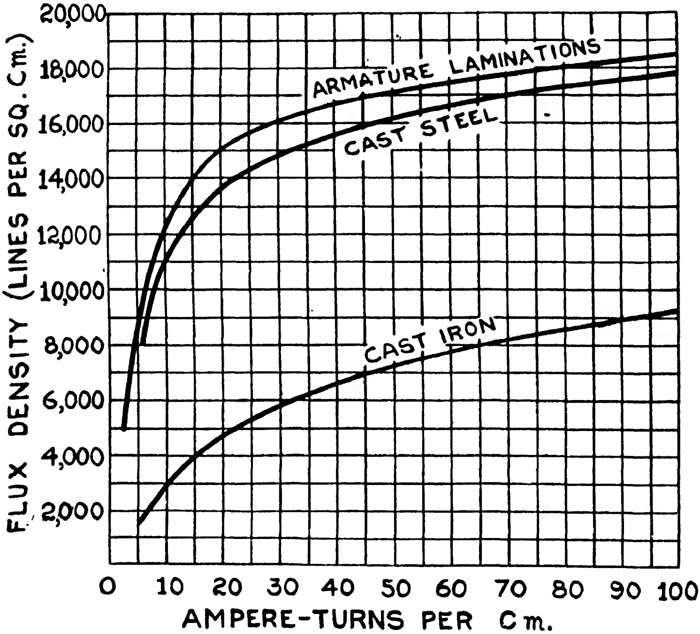


FIG. 153.—MAGNETIZATION CURVES.

For air the permeability is unity, so that ampere-turns per centimetre = 0·8 **B**. For iron and steel, however, the permeability varies with the quality of the metal, and also with every change in the value of the flux density. In order to find the ampere-turns required to send a given flux through a magnetic circuit of known sectional area and length, it is therefore necessary to find, first, the flux-density **B**, and then obtain the corresponding value of

μ from the permeability curve of the iron or steel of the quality it is proposed to use

A quicker method of determining the ampere-turns required is to plot a curve for different values of the flux density and the corresponding values of μ (from the permeability curve) as in Fig. 153.

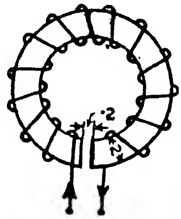


FIG. 154.—MAGNETIC CIRCUIT WITH AIR-GAP.

This figure gives directly the relationship between the flux density and the ampere-turns per centimetre length of the magnetic circuit. The three curves in Fig. 153 are for wrought iron armature laminations, cast steel, and cast iron respectively.

Ex. (*b*). An annular ring of cast iron with a mean diameter of 20 cms., has a circular cross-sectional area of 2 cms. dia. There is an air-gap of 0·2 cm. in the ring, as shown in Fig. 154, and the latter is wound with 500 turns of wire. Calculate the current required in the coil to produce a total flux of 12,500 lines, assuming that all the flux passes round the iron and across the air-gap.

Area of iron $= 0{\cdot}7854 \times 2 \times 2 = 3{\cdot}14$ sq. cms.

Flux density in iron $= \mathsf{F}/A = 12{,}500/3{\cdot}14 = 3980$ lines per sq cm

From the curve in Fig. 153 it will be seen that the number of ampere-turns required to send the above flux density through 1 cm of cast iron is 14·5.

Mean length of magnetic circuit in iron $= (3{\cdot}1416 \times 20) - 0{\cdot}2 = 62{\cdot}6$ cms.

The 0·2 cm. is subtracted as it belongs to the air-gap.

Ampere-turns required for iron $= 14{\cdot}5 \times 62{\cdot}6 = 908$.

If no fringing or leakage be allowed for at the ends of the ring, the flux density in the air-gap is also 3,980.

Then, ampere-turns for air-gap $= 0{\cdot}8\ \mathsf{B} \times l = 0{\cdot}8 \times 3980 \times 0{\cdot}2 = 637$ and, total ampere-turns $= 908 + 637 = 1545$.

Exciting current = ampere-turns/turns = 1545/500 = 3·09 amps.

The reluctance of a magnetic circuit, composed of different materials, may be written—

$$\mathsf{R} = \frac{l_1}{A_1\,\mu_1} + \frac{l_2}{A_2\,\mu_2} + \frac{l_3}{A_3\,\mu_3} \text{ and so on.}$$

Each portion is dealt with separately just as would have to be done for an electric circuit made up of pieces of wire of different lengths, areas and conductivities, all joined in series.

Ex. (c). The cross-section of a circular iron ring is 2 sq. cms. and its mean length is 37 cms., in which there is an air-gap of 2 mms. Find the flux produced by 1,968 ampere turns, if $\mu = 800$.

$$F = \frac{1\frac{1}{4} \times 1968}{\frac{36\cdot8}{2 \times 800} + \frac{0\cdot2}{2 \times 1}} = \frac{2460}{0\cdot023 + 0\cdot1} = 20{,}000 \text{ lines.}$$

156. RING CIRCUITS. It will be noted that there is no difference of magnetic potential between any two points in a closed ring uniformly and closely wound with an exciting coil. What happens is that on each lamina or thin plane at right angles to the axis of the coil there is an m.m.f., but the fall of magnetic potential across this lamina is equal to that m.m.f. A similar case sometimes the subject of discussion is a copper ring into the central space of which one pole of a long straight magnet is steadily pushed. An e.m.f. will be induced in the ring, and as it is a closed circuit of low resistance a large current will flow, or circulate round it. But there will be no p.d. between any two points, simply because each thousandth of an inch will have just the same e.m.f. induced, to create the current, as is equal to the pressure-drop caused by the current which flows. Hence in such examples we have instances of large fluxes and large currents, caused respectively by an m.m.f. and an e.m.f., but without any points between which there is a magnetic or an electric potential difference.

157. THE BRIDGE PRINCIPLE has been applied to the testing of iron. In Fig. 155 a closed magnetic circuit is made up of two yokes Y_1 and Y_2 and two turned bars S_1 being a standard sample whose **BH** curve is known and S_2 a sample of the iron to be tested. Round these are wound two similar magnetizing coils C_1 on the standard and C_2 on the test piece. If the magnetic fall of potential be the same in magnitude and direction on both bars, the ampere-turns in C_1 and C_2 will be the same. If not, then either the ampere-turns must be varied or some of the flux will leak out by Y_1 and Y_2 and produce a field between the horns h_1 h_2 which will cause the magnetic needle *ns* to deflect. Thus, by making the ampere turns on the sample give a magnetizing force necessary to produce a desired value of **B** in S_1, by varying the current in C_2 until *ns* does not deflect the magnetizing force required to give that value of **B** in can be found. By varying the current on C_1 another value of **B** is obtained and a further

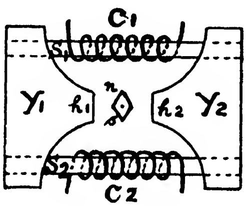


FIG. 155.—PERMEABILITY BRIDGE.

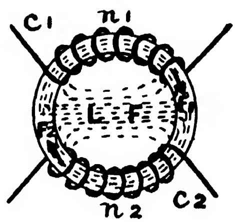


FIG. 156.—PRINCIPLE OF PERMEABILITY BRIDGE.

adjustment of C_2 will give a second point on the **H** curve for the test sample at the new flux density.

In Fig. 143 a ring was shown with one coil wound on a part of the magnetic circuit. In Fig. 156 a similar ring has two similar independent coils. The two figures side by side are magnetically alike. In the case of the ring if the two halves have similar reluctances the ampere-turns c_1 n_1 and c_2 n_2 must be the same if the flux F_1 produced by c_1 n_1 is to be the same as F_2 produced by c_2 n_2, in which case there will be no leakage flux **LF** across the ring. If the reluctances be different then the ampere-turns on top and on bottom coils must be proportional to these, otherwise there will be a difference between F_1 and F_2 which will appear as leakage flux **LF** across the ring.

158. MAGNETIC PULL. As lines of force tend to shorten themselves, there is a pull between two magnetized surfaces close together. The soft iron keeper or armature laid across the poles of a horse-shoe electro-magnet cannot be detached except by the exercise of force.

In the narrow crack or crevasse between a pole-face and its keeper there exists a flux-density **B**. This is measured by the force exerted upon a unit magnetic pole placed at the centre of each square centimetre. There are 4π lines emanating from a unit pole, and we have seen that $\mathbf{B} = 4\pi\,\mathbf{I} + \mathbf{H}$. **H** is so small compared with $4\pi\,\mathbf{I}$ that it can be neglected, while $\mathbf{I} = m/A$, and therefore for each square centimetre $\mathbf{B} = 4\pi\, m$, or $m = \dfrac{\mathbf{B}}{4\pi}$ which gives the strength for each square centimetre of the pole-face, or of the keeper, in terms of the flux density.

Between each square centimetre of the pole-face and the keeper there are **B** lines crossing the crevasse, and these lines we may say are produced equally by the two opposite faces, each giving $\dfrac{\mathbf{B}}{2}$ lines per square centimetre, or $\dfrac{\mathbf{B}}{2} \times A$ for the whole area A. The product of the pole-strength and the lines between the two faces will give the force or pull exerted—

$$F \text{ (in dynes)} = \frac{\mathbf{B}}{4\pi} \times \frac{\mathbf{B}}{2} \times A = \frac{\mathbf{B}^2 A}{8\pi}$$

Ex. (*a*). Which will exert the greater hold on force : a magnet having a flux of 400,000 magnetic lines and a contact surface of 8 sq. ins., or one having 500,000 lines and a contact surface of $12\frac{1}{2}$ sq. ins. ?

First, $F \propto (400{,}000/8)^2 \times 8 = 50{,}000^2 \times 8 = 20{,}000{,}000{,}000$.

Second, $F \propto (500{,}000/12{\cdot}5)^2 \times 12{\cdot}5 = 40{,}000^2 \times 12{\cdot}5 = 20{,}000{,}000{,}000$.

$\therefore$ the holding-on force is the same for both.

Ex. (*b*). A bar of iron, 1 in. sq., and 15 ins. long is made into a horse shoe magnet with centres of poles 3 in. apart. The pole-ends and keeper are faced to make good contact. What force is required to tear off the keeper, also of 1 sq. in. iron, if the excitation is 1,000 ampere-turns, and $\mu = 400$?

$l = 15 + 3 = 18$ in. and $18 \times 2{\cdot}54 = 45{\cdot}72$ cms.

$$\mathbf{H} = \frac{1{\cdot}25 \times 1000}{45{\cdot}72} = 27{\cdot}34$$

$$\mathsf{B} = \mu \mathsf{H} = 400 \times 27{\cdot}34 = 10{,}936 \text{ lines per sq. cm.}$$

$$F = \frac{10{,}936^2 \times 6{\cdot}45 \text{ sq. cms.} \times 2}{8 \times 3{\cdot}1416} = 61{,}400{,}000 \text{ dynes.}$$

$$= \frac{61{,}400{,}000}{445{,}000} = 138 \text{ lbs., force to tear-off keeper.}$$

Practical use is made of this force in *lifting magnets*, of which a typical example is illustrated in Fig. 157. Such

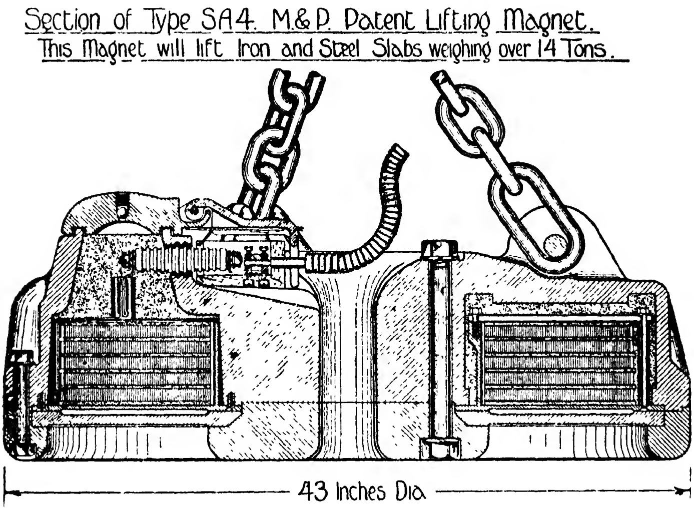


Fig. 157.—Lifting Magnet.
(*Marryat and Place.*)

a device is a sort of magnetic crane-hook and is used to lift ingots, steel plates, etc.

159. CYCLE OF MAGNETIZATION. So far, we have only considered what happens when iron is magnetized by magnetic forces of varying value, but all acting in the same sense or direction. Now we have to examine the effect produced by varying the magnetic force not only in strength but also in direction.

When any process is undergoing a change by which it returns over and over again to its original condition, the operation is said to be *cyclic*. Thus a train on the Inner Circle Underground Railway in London follows a *cyclic path*. Again the earth's movement round its orbit is a cyclic motion, for every 365th day it returns to its original position.

If, in addition to passing through a *cycle* or round of changes, the circumstances repeat themselves at regular intervals, and go through the same cycle over and over again, the process is termed a *periodic cycle*.

We may cause the magnetic force operating on a piece of iron to go through a cyclic change, by first increasing the current through the magnetizing coil in one direction till it reaches the highest value we intend to give to it, then slowly decreasing it till it reaches zero, then increasing the current in the reverse direction until it reaches the same maximum value as before (the direction of the lines being then opposite to that in the first case), and again slowly reducing the current to zero. This will have given us a complete *cycle of magnetization*, and the values of the magnetic force and the induction will have gone through a series of changes representing their cyclic values. If this process be repeated over and over again, we obtain periodic conditions such as occur with alternating currents.

160. HYSTERESIS. Electrical energy is momentarily expended in energizing an electro-magnet, quite apart from the constant expenditure of energy in overcoming the resistance of the coils. Part—but not all—of the momentarily-expended energy is given out again—on demagnetizing the magnet—in the form of an *extra current*; which is due to the momentary e.m.f. developed by the cutting of the turns of the coil by the collapsing lines of the field. The energy absorbed represents work done by the magnetic field of the current against inter-molecular friction, in setting the iron or steel particles in line.

The definition, *the lagging of a magnetic effect behind its cause*, conveys a fairly clear idea of the phenomenon of hysteresis. The magnetizations caused by gradually-increasing currents are always less than the magnetizations resulting from the same currents applied in a decreasing order. In soft or annealed iron the molecular friction is very small, hence the hysteresis in such iron is small. In iron that has been hardened in any way, as by drawing, hammering, by the addition of carbon (cast iron and steel), or chilling, the friction is greater. In the case of glass-hardened steel it is very great, so great—in fact—that it requires a comparatively large magnetizing force to turn the molecules at all; but when they are once turned, they remain in their new positions, and we have permanent magnets. The hysteresis in this latter case is enormous.

From the foregoing it will be seen that hysteresis means lost energy. It only becomes of importance, however, where the magnetizing forces vary periodically in strength, as in alternating-current work. In transformers, for instance, which are used for transforming alternating currents from higher to lower pressures, or vice versa, the phenomenon of hysteresis is very marked, and every endeavour is made to reduce it as much as possible.

The form of hysteresis referred to is sometimes termed *static hysteresis*, to distinguish it from *viscous hysteresis*. The latter effect is shown by the fact that an iron bar, subjected to a steady magnetizing force, does not magnetize up to its full amount all at once, the induction creeping up slowly till it reaches the maximum value it will take for the particular magnetic force applied.

161. HYSTERESIS CURVE. Fig. 158 shows the shape of a curve obtained when a sample of iron is subjected to a *cycle of magnetization*. Thus the exciting current is first sent round the coil one way, the current being gradually increased from zero to a maximum, and then gradually decreased again to zero. The current is then reversed and gradually increased, and once more reduced to nil; after which it is again sent in the first direction, until an area is enclosed by the curve.

The sample of iron is inserted in a coil of wire through which the current is passed, and the values of H for the different values of the current are calculated from $1\frac{1}{4}\ Cn/l$

At the same time the corresponding values of the induction **B** in the iron are found by means of the magnetometer (or some other) method. A curve plotted from the corresponding values of **B** and **H**, will have the general form shown in Fig. 158.

Values of **H** to the right of the vertical central line are due to currents in one direction, and those to the left of the line to currents in the opposite direction; the corresponding values of **B** being respectively above and below the horizontal line.

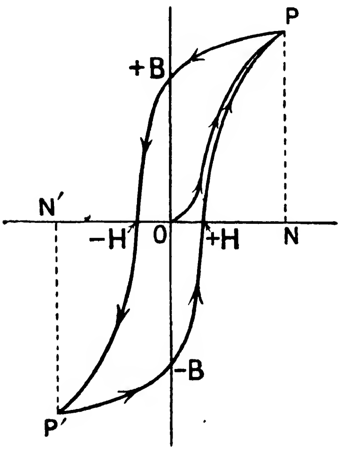


Fig. 158.—Cyclic Curve of Magnetization, or Hysteresis Curve.

To start with, we gradually increase the current from zero—marked *O*, and hence also the value of **H**, the induction **B** increasing as shown by that part of the curve from *O* to *P*; *PN* being the maximum induction obtained with the highest value of **H**, which is *ON*. On decreasing **H** to zero, the corresponding values of the induction in the sample are indicated by that portion of the curve from *P* to + **B**; and it will be noticed that for each value of **H** as the current decreases, the corresponding value of **B** is far greater than it was when we were increasing **H** from *O* in starting. Even when **H** reaches zero again, and no current is flowing round the coil, the induction is considerable and has a value of + **B**. This quantity represents the remanence or residual magnetism in the iron.

At *O* the current is reversed and slowly increased, the values of **H** being now plotted on the left-hand side of *O*, since they have an opposite or negative value. Here it will be seen that not until a magnetizing force of $-$ **H** is attained, is the induction **H** in the iron reduced to zero. This value of **H**, necessary for bringing the induction **B** in the iron back to zero after magnetization, is a measure of the retentiveness of the specimen, and is called the *coercive force.*

A further increase of **H** will result in the magnetizing of the iron so that the lines of induction flow in the opposite direction; and ultimately, when the value of **H** (ON') is equal but opposite to ON, the induction **B** of the iron will reach a point P' such that $P'N'$ will be exactly equal in length to PN.

In other words, when the magnetizing force is brought to the same value, first in one direction and then in the other, the corresponding values of induction will be exactly equal—though opposite.

The current is now again reduced to zero, and when this is reached, the induction will have a value $-$ **B** equal to and opposite to $+$ **B**, and will again be a measure of the remanence in the iron. The current is then again reversed and increased, until the induction once more reaches zero. The magnetizing force which corresponds to the zero induction will be $+$ **H**, and will again be a measure of the retentiveness of the specimen. The current being still further increased, until the magnetic force reaches its original maximum positive value ON, it will be found that the induction has once more reached the point P; and a complete cycle of magnetization will have been traversed.

If this cyclic process of magnetization be repeated a number of times, the curve will be retraced over and over again. Such a curve is called a *cyclic* **BH**, or *hysteresis curve.* Each time the process is gone through a certain quantity of electrical energy is transformed into heat, owing to the molecular friction or hysteresis of the iron. The amount of energy thus absorbed is proportional to the area enclosed by the curve; and this would obviously be greater in the case of a steel or cast-iron sample, than with a wrought-iron piece. In alternating-current work this *hysteretic loss* is continuous, and has to be taken seriously into account.

Fig. 159 shows actual curves taken from a specimen of dynamo-magnet steel. Any number of hysteresis curves can be obtained, depending upon the maximum value of **H** at which the direction is reversed. Thus, in the two

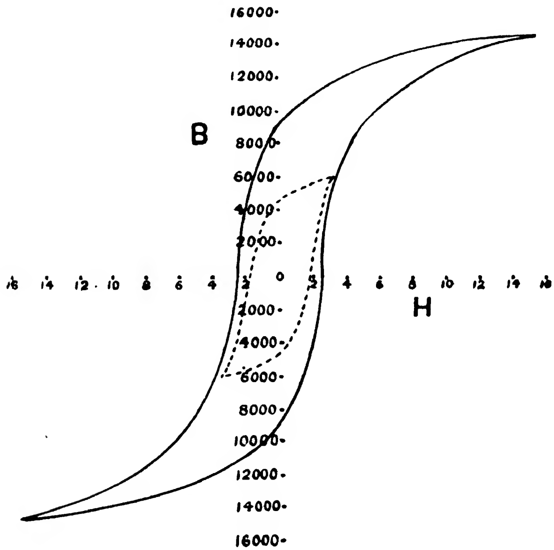


FIG. 159.—HYSTERESIS CURVES FOR DYNAMO STEEL.

shown, the dotted one was obtained by reversing when **H** = about 3, and the full line one when the increase was continued until **H** = about 16.

The curves shown refer to *static hysteresis*. *Viscous hysteresis* is another effect which shows that the induction lags behind the magnetizing force by an interval of time, but gradually creeps up to its maximum value if the force be steadily maintained for a sufficient period. It follows from this that in making a **BH** or hysteresis test, the area enclosed by the curve will be less if the observations are made directly the current value is altered, than if an interval of time be allowed to elapse before noting the deflection values of the ammeter and magnetic needle. As most hysteresis tests are on samples of iron to be used in alternating-current work, the readings of the current and magnetometer deflections should therefore be taken without delay. An ordinary alternating current does not give time for the viscous hysteresis to die away, so that this form of hysteresis must be included in the test.

With a given iron core magnetized by an alternating current, the loss of energy due to hysteresis will be the greater the higher the frequency of the current.

162. EWING'S HYSTERESIS TESTER. In alternating-current apparatus, the *hysteretic loss* must be kept as low as possible; a low hysteresis value being of more importance than high permeability. A sample of iron which possesses high permeability has not necessarily a low hysteresis value.

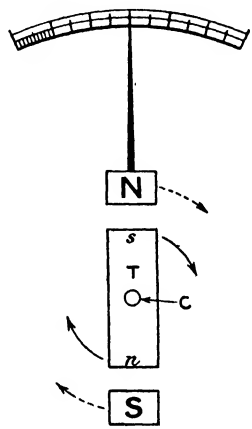


FIG. 160.

To find the hysteresis value of any sample by the method described in the preceding section is a lengthy process; but with this instrument the test consists of little more than the turning of a handle.

In Fig. 160, N S is a permanent horseshoe magnet suspended on a knife-edge about a centre *c*, and with its poles facing the observer. This magnet is kept in a vertical position by gravity, and has a pointer fixed to its upper pole. *T* is the test-piece, formed of a number of thin sheet pieces of the iron under test, these being tightly clamped together in a holder and pivoted about a centre *c*, in line with, but separate from, that on which the magnet

N S turns. T is geared-up with a hand-wheel in such a manner that it can be rotated rapidly either way. When this is done, say in the direction shown by the curved arrows, the magnet will turn in the same direction. The exact rate at which the handle is turned is immaterial, provided it is sufficient to give a steady deflection. The amount of this deflection—as indicated by the pointer on the scale—will be proportional to the hysteresis of the test-piece T.

T being built up of a number of flat sheets, is laminated in the direction in which induced currents would tend to be set up. In the position shown, the lines passing from N to S induce south polarity at s and north polarity at n. When T turns so that n approaches N and s approaches S, the poles N and S will have to reverse the polarity of the approaching poles. But the greater the hysteresis, the longer will the approaching poles retain their polarity; and the greater will be the repulsion set up between these poles and those of the permanent magnet. Once the poles have been reversed, repulsion—proportional to the hysteresis—will again be set up as they approach their original position. Work has to be done in rotating the test-piece against this repulsion, and the amount of this work done, in constantly reversing the magnetism of the test-piece, is shown by the deflection of the permanent magnet against the force of gravity.

The instrument is illustrated in Fig. 161, and its construction is described by an index of parts.

Two standard samples are furnished with each instrument, and pieces of the sheet to be tested having been cut to $\frac{5}{8}$ in. wide and 3 in. long, enough of these are taken to equal the weight of a standard piece, and then clamped in the holder.

The handle is then turned at a moderate speed and the deflection noted; the direction of rotation is then reversed and the second deflection noted. The sum of these two deflections is taken as the result.

The standards have their hysteresis values (in watts per lb. or ergs per c.c. at a certain induction and frequency) given by the makers. These are put through the same test, and two points giving the relation between the hysteresis and deflection for each are marked on squared paper. A straight line is projected through these points, and knowing the deflection of the test-piece, the equivalent hysteresis of the sample is found from the curve.

P = Permanent magnet.
K = Knife edge.
p = Pointer.
S = Scale.
t = Thumbscrew.
d = Dash-box.
T = Test-piece.
F = Friction pinion.
H = Hand wheel.

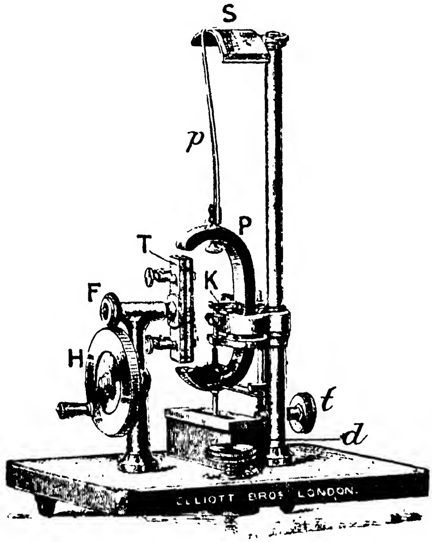


Fig. 161.—Ewing's Hysteresis Tester.

For example, the curve might be obtained with two pieces which were standardized at an induction **B** of 4,000 and frequency (~) of 100; *A* having a hysteresis loss of 0·53, and *B* a loss of 1·46 watts per lb. The hysteresis values obtained from the test-pieces will therefore be the equivalents for the same induction as marked on the standard pieces, in this case 4,000. They may be converted into equivalents for other values of **B** by multiplying by the factors in the left-hand table below. Thus if a specimen tested on the Ewing apparatus gives ·8 watts per lb. with standard pieces at B = 4,000, its value when B = 6,000 will be ·8 × 1·89 = 15·1 watts per lb.

Similarly the hysteresis values may be converted into equivalents for other frequency values by multiplying by the factors in the right-hand table below, assuming that the standards were standardized at 100 ∼. Watts per lb. at 100 frequency divided by 0·0006 = ergs per cubic centimetre per cycle.

B	Relative Hysteresis.
2,000	0·33
2,500	0·47
3,000	0·63
4,000	1·00
5,000	1·41
6,000	1·89
7,000	2·41
8,000	3·00

∼	Relative Hysteresis.
100	1·00
80	·8
60	·6
50	·5
40	·4
25	·25

A loss of ⅔ of a watt per lb. with B = 10,000 and a frequency of 50 complete reversals per sec. is the sort of figure often obtained in practice.

QUESTIONS

1. Distinguish shortly between the electric and magnetic circuits, and show how they interlink.

2. Distinguish between paramagnetic and diamagnetic bodies, and between lines-of-force and lines-of-induction.

3. It is found that the magnetism in the iron core of an electromagnet does not entirely disappear when the current ceases; to what cause is this attributable?

4. In choosing metal for a dynamo field-magnet, and for a large electric bell respectively, would it matter if that selected had slight retentiveness?

5. Compare the leakage in a magnetic circuit with that in an electric circuit composed of an hermetically-sealed battery and a naked-wire circuit immersed in the sea.

6. Give the definition of the terms "magnetic lines of force" and "the intensity of a magnetic field." Why do the patterns obtained by sprinkling iron filings on cardboard or glass not accurately represent the magnetic lines of force?

7. How can you magnetize a steel ring so that it may have poles at opposite ends of a diameter?

8. If you have a small electromotive force, and no appreciable resistance in the rest of the circuit, would you select as an electromagnet one wound with many turns of fine wire, or one wound

with few turns of thick wire? Under what circumstances would you use one having its core made up of a number of stampings of sheet iron?

9. Explain what is meant by the terms: magnetizing force, magnetic flux, and flux-density. What materials would you use for (*a*) the pole-core of a dynamo, (*b*) the armature core of a dynamo, and (*c*) a permanent magnet?

10. State what is meant by the terms magnetic resistance and permeability of iron, and by saying that the permeability of soft wrought iron is greater than that of cast iron.

11. What considerations would guide you in the selection of an iron for the field-magnets of a dynamo? What are the respective merits of steel, wrought iron, and cast iron for dynamo field-magnets?

12. What is a magnetization curve? Show by curves the magnetic properties of mild cast steel, hard steel, wrought iron and cast iron. Show also, besides their respective capabilities of receiving magnetization, their respective capabilities of retaining it.

13. Draw characteristic B H curves on the same scale for cast iron and sheet steel, and mark the scales for the ordinates and abscissae.

14. Show by means of curves the approximate numerical relations between magnetic induction and permeability for good specimens of cast iron, wrought iron, and cast dynamo-steel respectively.

15. Show how a law, similar to that of Ohm, may be applied to the magnetic circuit; and show also that it is only roughly correct.

16. What magnetic quantities are denoted by the symbols H, B, and μ; and how are they related to one another?

17. A certain coil of wire carries a constant direct current; how would you ascertain the value of H?

18. What is the rule for calculating the intensity of the magnetic field in the middle of a long tubular solenoid? If the winding is uniform all along, what is the intensity of the field at the open ends as compared with that in the middle? Where must an iron bullet be placed so that the force exerted on it by the solenoid shall be a maximum?

19. What do the terms "intensity of field" and "ampere turns" mean? Calculate the intensity of the field at the central point of a solenoid 100 cms. long, of small diameter, wound with 6,000 turns of wire traversed by a current of 5 amperes. *Ans.* 375.

20. Calculate the magnetic field at the centre of a long bobbin of wire, consisting of one layer, making 1,000 turns, and wound on a tube 2 metres long and 4 centimetres in diameter, traversed by 10 amperes. How many lines of force are embraced by the central portion of the solenoid? *Ans.* 62·5: 785·4.

21. You have to make a long coil of wire such that when 10 amps. flows through it the magnetic field in the centre shall be 1,000 times as strong as the earth's horizontal field (*H*). How many turns per centimetre must be put on the coil? *Ans.* 14·4.

22. You are required to wind over a brass tube, 500 centimetres long and 2 centimetres in external diameter, with one layer of covered wire, 1 mm. diameter over the covering. What will be

the strength of the magnetic field at the centre of the axis of such a helix when a current of 1 ampere flows through the wire ? *Ans.* 12·5.

23. Describe the kind of tests you would make to ascertain which of a number of specimens of iron was the most suitable for use as cores of electro-magnets. State what qualities you would desire to find present, in order to approve of a sample as good.

24. Define the terms "magnetizing force," "flux," and "flux-density." Explain a simple method of finding the permeability of an iron bar.

25. How may the magnetic permeability of a sample of iron be determined if the sample is in the form of a ring ? State what apparatus is required for the test, and explain how **B** and **H** for the iron are measured.

26. Sketch and describe an instrument for the commercial testing of the permeability of iron of different brands.

27. Show the general form of a permeability curve for iron, and give a brief description of a measurement by means of Drysdale's permeameter.

28. Define magnetomotive force, permeability, and reluctance. Show that the flux in a magnetic circuit is directly proportional to the magnetomotive force acting on the circuit and inversely proportional to the reluctance of the circuit.

29. When an electric circuit is interlinked with a magnetic circuit, state the relation which exists between current, e.m.f., magnetomotive force, magnetizing force, flux, and flux-density.

30. An iron ring of 10 cms. mean diameter and 1 sq. cm. cross-sectional area is wound with 100 turns of wire. What will be the value of the magnetic induction in the iron when a current of 3 amps. flows in the wire ? Take the permeability of the iron as 800. *Ans.* 954·9.

31. An iron ring forms a closed magnetic circuit, having a mean length of 30 cms. and a section of 1·5 sq. cm. On the ring are wound 100 turns of insulated wire, and 1 amp. in the wire gives a total flux of 12,000 lines in the ring. Find the permeability of the iron. *Ans.* 1,920.

32. Calculate the number of ampere-turns of excitation required to magnetize up to 14,000 lines per sq. cm., a soft iron ring, 20 in. in mean diameter, made of round iron 1 in. thick. Assume permeability = 800. *Ans.* 2,235.

33. A flux-density of 10,000 lines per sq. cm. is required in an iron ring of 5 sq. cm. cross-section and 20 cms. mean diameter. If the permeability at this flux-density is 1,000, and the ring has 500 turns, calculate the exciting current. How would the exciting current be affected if the cross-section were halved, other things remaining the same ? *Ans.* 1·0053 amp. ; would not be affected.

34. A soft iron ring, 100 cm. mean circumference and 5 sq. cms. cross-section, is uniformly wound with 200 turns of insulated wire. Suppose you have found that the following relations exist in iron of this quality—

B =	10,200	12,000	13,700
μ =	2,000	1,500	1,000

Calculate the current C at which the total flux is 65,000 lines. *Ans.* for 1,700 μ goes down 500, so at $\mathsf{B} = 65000/5 = 13000$, $\mu = 1206$, and $C = 4{\cdot}312$ amps.

35. A stalloy ring has a mean circumference of 50 cms. and is uniformly wound with 100 turns of insulated wire. The cross-section of the ring is 1 sq. cm. Find the current in amperes required to produce a value of the magnetic flux-density in the ring of 5,000, having given the following relation between the magnetizing force and the permeability—

$\mathsf{H} = 0{\cdot}677$	$0{\cdot}834$	$1{\cdot}35$	$2{\cdot}13$
$\mu = 3{,}320$	4,200	4,470	3,850

Ans. 0·456 amp. Since $\mathsf{B} = \mu\mathsf{H}$, a B H curve could be drawn with values as follows—

$\mathsf{B} = 2{,}248$	3,503	6,034	8,200

As $\mathsf{B} = 5{,}000$, assuming a straight-line law for the interval between 3,503 and 6,034, the corresponding value of H would be

$$\left(\frac{1497}{2531} \times 0{\cdot}516\right) + 0{\cdot}834 = 1{\cdot}1392. \quad \text{Then } \mathsf{H} \times l = 1{\cdot}25\,Cn.$$

36. Define magnetizing force and magnetic induction, and state the relation between them. How many ampere-turns are required for an air-gap 200 sq. cms. in area and 5 mm. long when the magnetic flux is 1 megaline ? *Ans.* 2,000.

37. A circular iron ring forms a closed magnetic circuit whose mean length is 37 cms. and whose cross section is 2 sq. cm. Find how many ampere-turns must be provided to produce a total flux of 20,000 lines in this circuit, the permeability of the iron being 800. Show how the problem is altered if an air gap of 2 mm. width is introduced into the magnetic circuit. *Ans.* 370 amp-turns; 1,968 amp-turns.

38. A ring-shaped electro-magnet has an air-gap 6 mm. long and 20 sq. cms. in area, the mean length of the core being 50 cms., and its cross-section 10 sq. cms. Assume permeability of iron as 1,800, calculate approximately the ampere-turns required to produce a field of strength, $\mathsf{B} = 5{,}000$ in the air-gap. *Ans.* 2,622.

39. Estimate the number of ampere-turns necessary to produce a flux of 85,000 lines round an iron ring of 5 sq. cms. cross-section and 25 cms. in mean diameter, having an air-gap of 2 mms. wide cut across it. $\mu = 425$. *Ans.* 5,227.

40. A soft iron bar 2 cms. in diameter is made into a circular ring of 20 cms. mean diameter. An air-gap of 0·2 cm. is cut across the ring. Calculate the excitation required to produce a flux of 48,000 lines in the gap if the permeability of iron is 600, and the number of turns in the coil is 1,000. *Ans.* 3·72 amps. Check is

$$\mathsf{F} = \frac{1\tfrac{1}{4} \times 3{\cdot}72 \times 1000}{\dfrac{62{\cdot}63}{3{\cdot}14 \times 600} + \dfrac{0{\cdot}2}{3{\cdot}14 \times 1}} = 48{,}000$$

41. An iron ring 25 cms. in diameter and 4·5 sq. cms. in cross-section is wound with 500 turns of wire; it has an air-gap 0·25 mm. wide in it. If $\mu = 700$, what current must be sent through the coil to produce a flux of 45,000 lines across the air-gap? *Ans.* 2·1944 amps.

The data from the five questions given above are collected in the following table and the student should work out each of the quantities, and also note how the ampere-turns vary with different values of B and μ.

Q	Air-gap.			Iron.				
	l	B	CN	l	μ	CN per cm.	H	CN
37	0·2	10,000	1,600	36·8	800	10	12·5	368
38	0·6	5,000	2,400	50·0	1,800	4·4	5·5	222
39	0·2	17,000	2,720	78·3	425	32	40·0	2,507
40	0·2	15,279	2,445	62·6	600	20·4	25·5	1,276
41	0·025	10,000	200	78·5	700	11·4	14·3	897

In the air-gap $CN = 0{\cdot}8\ Bl$ and in the iron CN per cm. $= 0{\cdot}8\ B/\mu$ while the ampere-turns on the iron $CN = 0{\cdot}8\ Bl/\mu$. In Q. 38, B is 5,000 in the air-gap and 10,000 in the iron. In the other examples the flux density is the same in the iron and in the air-gap. If these amp.-turns per cm. and flux-densities are marked on Fig. 153 they will be found to fall very nearly on the curves.

42. In electro-magnets for removing particles of iron from the eye the pole-pieces are coned to a smooth point. What is the reason for this particular shape?

43. The area between a bar electro-magnet and its keeper is 1 sq. cm. and the flux-density 10,000 lines per sq. cm. What is the force with which the magnet attracts the keeper? *Ans.*, 8·942 lbs. *Note.*—This is a useful figure to memorize as a check upon calculations.

44. Two bars, each 5 sq. cms. in cross-section, have their faced ends touching within a solenoid excited so as to produce a magnetic induction of 15,000 lines per sq. cm. through the joint. Give, in lbs., the force requisite to pull them apart. *Ans.* 100·59 lbs.

45. Describe the construction of a plunger electro-magnet. Calculate the pull in lbs. exerted on a plunger 2 in. in diameter, when 200,000 lines of force from a fixed core pass into the end of the plunger at uniform density. *Ans.* 176·5 lbs.

46. A horse-shoe electro-magnet, with a core and keeper forged from 1 in. sq. iron, is excited by 300 ampere-turns. The joints make a perfect fit, and $\mu = 1{,}500$. The length of the magnetic circuit is 16 in. Find the force required to tear the keeper off. *Ans.* 110·5 lbs.

47. Two semi-circular pieces of round iron 5 sq. cms. area are made into a ring electro-magnet by being wound with 250 ampere-turns, the length of the magnetic circuit being 50 cms. The force required to separate the two halves when in good contact is 4 kgs. Find the permeability of the iron. *Ans.* Total area = 10 sq. cms.; $\mathsf{H} = 6{\cdot}25$; $\mathsf{B} = 3140{\cdot}3$, $\therefore \mu = 502{\cdot}45$.

48. The total area of two poles of an electro-magnet is 223 sq. cms., the magnetic path in iron 91 cms., the flux-density 15,000 lines per sq. cm., and the corresponding permeability 650. Find (*a*) the load in tons which the keeper will support at its centre, (*b*) the necessary excitation when the keeper is separated from its poles by brass of a total thickness of 0·5 mm. *Ans.* (*a*) 2 tons; (*b*) 2,280 amp-turns.

49. What is the cross-section of the steel, and the number of turns and size of wire in the exciting coil of an electro-magnet of the horseshoe type, which has to support a weight of 1 ton from the centre of its keeper, the latter being separated from its poles by a brass distance piece, 1 mm. thick? The mean magnetic path is 100 cms., the flux-density 15,000 lines per sq. cm., the permeability 650, the mean length of one turn 50 cms., the supply voltage 100 volts, and the permissible power to be dissipated 100 watts. *Ans.* 55·67 sq. cms.; 4,242 turns; 0·000557 sq. in.

50. Give a short account of the general nature of the magnetization phenomena observed when bars and rings of soft iron are carried round complete magnetic cycles. How does hysteresis cause waste of energy in a transformer?

51. What do you understand by the term hysteresis? Distinguish between static and viscous hysteresis.

52. Explain briefly the reason why reversing the direction of magnetization of a piece of iron requires a certain expenditure of energy.

53. Sketch the general form of a curve connecting H and B when a soft iron ring is carried through a magnetic cycle, the flux-density being brought up to 10,000 c.g.s. lines per sq. cm. in one direction and to − 10,000 in the other direction, and so on.

54. Are you acquainted with any method of ascertaining the hysteresis value of a specimen of iron other than that adopted in Ewing's hysteresis tester? If so, compare the methods.

55. Describe, with diagram of connections, some method of determining the hysteresis loop for an iron anchor ring.

56. Distinguish between the energy absorbed in energizing an electro-magnet, and that given out on demagnetization.

57. How are the pull and self-induction of an electro-magnet connected?

58. Explain exactly what you mean by the inductance of a coil with an iron core (*a*) when the permeability of the iron is constant, (*b*) when the iron is saturated and the permeability varies for each new value of the flux density.

CHAPTER VII

STANDARDS AND MEASUREMENTS

163. ELECTRICAL STANDARDS. The Board of Trade is authorized by the Weights and Measures Act, 1889, to cause new standards to be made for use in trade. Electricity, or, strictly speaking, electrical energy, is "goods" in a legal sense, and it is bought and sold. The units by the use of which such sale takes place are the ohm, the ampere, and the volt, and these have their place in our measures under an Order in Council of 1910.

The international **ohm** is the resistance offered to an unvarying electric current by a column of mercury at a temperature of melting ice, 14·4521 grammes in mass, of a constant cross-sectional area and of a length of 106·3 cms. Formerly it was thought that the ohm could be represented by a metre length of mercury of 1 sq. mm. cross-section, but as purer mercury has been obtained the length has had to be increased to retain the same resistance. It is difficult to measure an area, and the more logical way of defining the mass, or quantity, is now adopted.

The international **ampere** is the unvarying electric current which, when passed through a solution of nitrate of silver in water, deposits silver at the rate of 0·001118 gramme per second. In checking by this method, an anode of silver about 30 sq. cms. in area and 2 or 3 mm. thick is supported horizontally in a solution of 15 parts of nitrate to 85 parts of water contained in a platinum bowl, about 10 cm. diameter and 4 or 5 cms. deep, as kathode. Current is allowed to pass for half an hour, and the bowl, with its deposited silver, is washed and dried. The current, which must have been kept steady during the test, is equal to the weight of silver in grammes deposited, divided by number of seconds the current has been on, multiplied by 0·001118.

The international **volt** is the electrical pressure which, when steadily applied to a conductor whose resistance is 1 international ohm, will produce a current of 1 international ampere.

164. THE LEGAL STANDARD OF RESISTANCE is the resistance between the copper terminals of an instrument marked "Board of Trade Ohm Standard, verified 1894 and 1909," to the passage of an unvarying electrical current when the coil of insulated wire forming the conducting part is at a temperature of 16·4° C. This, with the other two standards, used to be kept in the electrical laboratory of the Board of Trade, and is now at the National Physical Laboratory. The limit of accuracy attainable in the use of the standard of resistance is one-hundredth part of 1 per cent. To attain to anything like one-tenth of 1 per cent needs care, and, to do better than this, very great care.

The term "resistance" has two electrical meanings: (*a*) the property itself, and (*b*) the thing which has the property.

165. RESISTANCE COILS, or, as they are sometimes called, resistors, are employed to regulate or control the current which flows in a circuit; or to limit the maximum current which can flow; as shunts to current measuring instruments; or as standards, sub-standards, or working copies of these when testing the resistance of cables, lamps, and other appliances, or when locating faults on mains. Resistances are used to dissipate energy when "loading-up" dynamos or transformers.

The "rating" of coils, or the current they can safely carry, depends upon the time that current is permitted to flow through them and on the current density. Thus, for intermittent use, much higher currents can be safely carried by a given coil than would be the case if the flow of current were uninterrupted.

Resistors may be divided into three classes: metallic, carbon or graphite, and liquid. The construction of metallic resistances is an art in itself. There are a number of metals and alloys to select from ; the resistance material may be in the form of wire, ribbon, tube, stamped or cast grids, or netting ; and the methods of mounting, insulating, and connecting up are numerous.

Spiral coils of wire, simply suspended in the air, are so unreliable, through the metal becoming crystalline and breaking, and they take up so much room, that they are only used in the cheapest grades of resistances or where fairly large currents at considerable voltages have to be carried continuously, and no other form gives space for insulation and the necessary surface for getting rid of the heat produced. As wires extend on being heated, the coils must have room to expand freely, or some device must be provided for taking up the extension.

The three essentials in the construction of resistance coils are : (*a*) They must be effectively insulated and properly supported, so that the insulation is maintained. (*b*) If permanency be desired, they must be protected from the air and the acids which, in an industrial district, are always present in it. This protection may be paraffin or bees-wax, where the wire will not be heated appreciably in use ; or insulating oil ; or some enveloping cement or enamel where such large currents have to pass through the wires as will heat them up to a higher temperature than the melting point of wax. (*c*) Some means (such as ventilation, or circulation of oil) must enable the heat developed in the wire to be got rid of.

As a consequence of these requirements, the forms resistances take are very varied, ranging from strips of platinoid or manganin held between brass or copper terminal blocks, to spiral coils wound on supporting tubes and embedded in some insulating heat-conducting enamel ; and, finally, to very long coils of high resistance wire, insulated with silk and buried in wax. Large current resistances are often either strips of metal, corrugated to give them mechanical strength, or wires held in position by asbestos woven to form a fabric having the insulation crossing the conductors at right angles. The wires are run up and down in a close zig-zag, and are interwoven crossways or from side to side by asbestos yarn. This keeps the neighbouring lengths of wire well apart and stiffens the whole construction.

Resistances for wattmeters and voltmeters sometimes consist of insulated wire strung backwards and forwards over a large number of porcelain bobbin insulators, carried on supporting rods in a metal frame.

Any number of stamped resistance grids may be mounted and connected in frames. In the " cracker " type, a zig-zagged, naked, corrugated strip is used, and this is threaded through the middle on an insulated rod with insulating separators, the whole being clamped between nuts. The grid type of resistor gives a large radiating surface, and therefore a small weigh for a given capacity, hence such resistors cool very quickly, while freedom is allowed for expansion with changes of temperature. There are few joints to be looked after, thus there is little trouble from vibration. Any one grid can be renewed, and " taps " or connections may be taken off at intervals as required.

Difficulty is so often caused by joints that a type of resistor has been introduced in which the grids are jointless for a " bank " or " nest." As many as 26 grids may be cast together, with only two ends and no intermediate joints.

The simplest resistance for dissipating energy is a tub of water. rendered more conducting by having a few handfuls of salt thrown into it. Large powers can be dissipated by wooden troughs, a supply of cold water being pumped in at one end and allowed to flow out over a sill at the other end.

166. STANDARD RESISTANCES are copies of the legal standard in so far as resistance is concerned, although they may be made up in various forms, all devised to secure permanency, and are sent out carefully adjusted by the makers. They have some known exact value in ohms at a given temperature, and are generally made of platinum-silver or manganin wire covered with white silk. Although platinum-silver is the more constant in resistance, when length of service is taken into consideration, manganin wire is suitable for most coils, as it has about twice the specific resistance and changes less with change of temperature.

Before being wound on its supporting bobbin, the silk-covered wire is baked in an oven and boiled in paraffin wax, to get rid of moisture and improve the insulation of its covering.

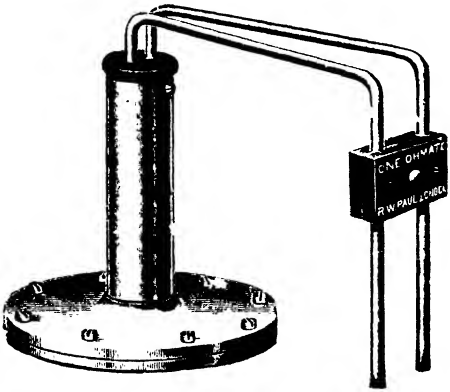


FIG. 162.—STANDARD RESISTANCE COIL.
(*Paul type.*)

A standard coil is wound non-inductively upon a bobbin and, after being again dipped in paraffin wax, is enclosed in a brass case, its ends being connected to thick copper legs outside. Only comparatively small currents must be passed through standard resistance coils, otherwise the heat evolved will alter the resistance of the coil, a slight variation being sufficient to affect the accuracy of a measurement. In the form shown (Fig. 162), the wire (of platinum-silver with a double covering of pure white silk) is wound in a flat double spiral, and enclosed in a thin, flat, water-tight box, so that it may be immersed in a water or oil bath. The coil, which is insulated from the box by mica, quickly takes the temperature of the water, owing to the large surface exposed, and its flat shape. The coil is correct at a certain temperature, generally 15° C.

167. RESISTANCE BOXES for ordinary measurements are made with coils of platinum-silver, manganin, platinoid, or German silver. A number of coils, having varying values, are frequently combined in one piece of apparatus, just as a set of weights are used with balances. The values may be 1, 2, 2, 5 or 1, 2, 3, 4 ohms, and so on; the object being to obtain any resistance between 1 and 10 ohms, going up by 1 unit at a time. Or the combination may be 10 coils of 1 ohm each connected in series and joined up with some switch or plug arrangement, enabling any required number to be inserted in the circuit. The coils are generally contained in boxes, as shown in Fig. 163. The brass blocks *B*, *B*, *B*, mounted on a slab of ebonite, are in connection with the coils through the straight wires *W*, *W*, *W*; and any coil can be inserted in or cut out from the circuit at will, by means of the brass plugs *P*, *P*, which are fitted with insulating handles. When the plugs are in between *B*, *B* they *short-circuit* the coil connected to these blocks. Resistance coils constructed in the above manner are wound non-inductively and are used for various tests. The currents passed through them never exceed some small fraction of an ampere, and only intermittently.

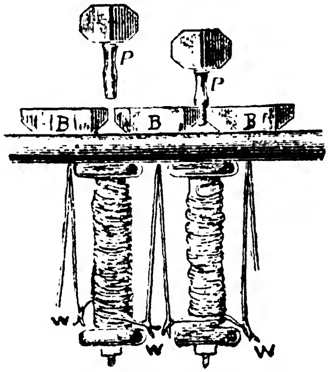


FIG. 163.—RESISTANCE COILS.

The largest currents which can safely be passed through testing resistance coils for a period of not exceeding a minute or two, are in the order of—

Ohms.	Units.	Tens.	Hundreds.	Thousand.
Currents	1 amp.	0·25 amp.	0·125 amp.	0·025 amp.

There is another class of standard resistance, which is used for carrying a current continuously, especially in connection with measurements on the potentiometer principle. Such resistances consist of a number of thick wires or strips of manganin soldered into massive terminal blocks of copper. For very heavy currents the manganin conductor is made in the form of a tube, and arrangements are made for passing water through in order to keep the resistance cool. Such resistances can carry currents up to thousands of amperes without overheating. Fig. 164 shows a water-tube standard resistance.

FIG. 164.
(Crompton.)

Resistances of this class are always provided with two pairs of terminals. One pair is fitted at the ends of the resistance—for the connection of the leads conveying the current (current terminals); and the other pair, which is smaller (potential terminals), makes contact at two intermediate points. A standard resistance of this class has a value = p.d. between potential terminals/current through current terminals.

All resistances should have marked on them their maximum carrying current, and value in ohms at a stated temperature.

168. HIGH RESISTANCES. A wire megohm resistance is often made with 10 coils of 0·1Ω connected between six terminals in each of two rows, the two rows being joined by the strap *d*. This gives several combinations: When all are in series between the leads l_1 and l_2 the total resistance is 1Ω, as in Fig. 166. By shifting the connection of one of the line-wires along the terminals the resistance is reduced by steps of 0·1Ω until, when only one section is in circuit, the resistance is 0·1Ω. Intermediate values can be obtained by such combinations as 0·2Ω in parallel with 0·8Ω when the joint resistance is 0·16Ω, obtained by l_1 on c and l_2 joined to both a and b terminals. With l_1 joined at d and l_2 to a and b, the two halves of the resistance are in parallel, giving ¼Ω.

Resistances below 0·1Ω can be obtained by a parallel connection of the sections until, finally, when joined up as in Fig. 165, with all odd terminals connected to l_1 and all even terminals to l_2, the joint resistance is 0·1Ω/10, or 0·01Ω. A useful exercise for the student would be to find how many different joint resistance values can be obtained from such a megohm box, and what they are.

169. VARIABLE RESISTANCES. It is often required to insert resistances in a circuit for the purpose of absorbing

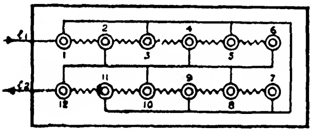


FIG. 165.

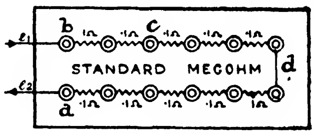


FIG. 166.

power (load resistances) or cutting down the current; and, in such cases, it is seldom necessary to know their exact value, though they must be capable of adjustment to higher or lower values. Coils of iron wire, carbon or metal plates dipping into water, etc., are useful for this purpose. A "regulating resistance" is one giving gradations of resistance in the circuit, usually by a small change for each step or contact.

If current is taken from a public supply, an arrangement of switches and lamps, which will be found useful as a variable resistance, is shown in Fig. 167. **S** is a row of tumbler switches and **L** a row of lamp holders. These are connected in parallel across the terminals **T**, **T** +, each set consisting of a switch in series with a lamp holder. A third terminal, **T** –, is connected through the main switch **MS** and fuse **F** with a fourth terminal **T′**. **T** and **T′** are joined up by wires **W** with the distribution board in the building. The apparatus for which current is required is connected to the terminals T + and T –. Lamps being inserted in the holders, the current flowing can be regulated by turning on one or more of the switches S. By using

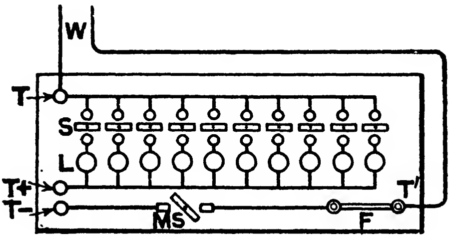


Fig. 167.

lamps of lower or higher candle power, the additions of current when the switches S are put " on " can be regulated as desired.

A cheap way of getting more variation in resistance with a given number of lamps is illustrated in Fig. 168.

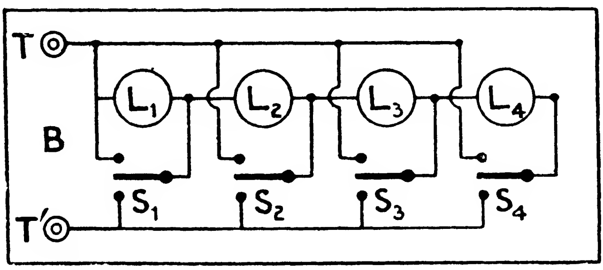
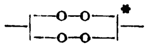
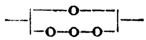
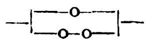
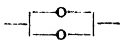
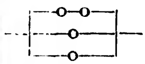
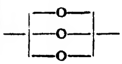
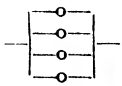


Fig. 168.—Lamp Variable Resistance.

Here, L_1, L_2, L_3, L_4 are lamps mounted in " batten " holders, i.e. short holders fitted with lugs to enable them to be screwed down to the wooden base *B*. S_1, S_2, S_3, S_4 are two-way tumbler switches with " off " positions ; and the lamps and switches are connected to the terminals *T* and *T′*. If S_1, S_2, S_3, or S_4 be put on its bottom contact, 1, 2, 3 or 4 lamps respectively will be connected in series across the terminals. If S_1 and S_3 be placed on their bottom contacts, and S_2 and S_4 on their top contacts, all the lamps will be in parallel. Altogether there are eleven possible arrangements, as detailed in the following table;

Bottom Contact.	Top Contact.	Arrangement of Lamps.	Circuit through Lamps.	Resistance in Circuit with lamps each having a cold resistance of—	
				100 ω.	200 ω.
				ohms.	ohms.
$S4$	—	4 in series.	—o—o—o—o—	400	800
$S3$	—	3 ,,	—o—o—o—	300	600
$S2$	—	2 ,,	—o—o—	200	400
$S1$	—	1 ,,	—o—	100	200
$S2$	$S4$	2 parallels of 2 in series.	 *	100	200
$S3$	$S4$	1 in parallel with 3 in series.		75	150
$S2$	$S3$	1 in parallel with 2 in series,		66·7	133
$S1$	$S2$	2 in parallel.		50	100
$S2$ & $S4$	$S3$	2 in series in parallel with 2 in parallel.		40	80
$S1$ & $S3$	$S2$	3 in parallel,		33·3	66·7
$S1$ & $S3$	$S2$ & $S4$	4 ,,		25	50

and if the number of lamps and switches be increased, the number of available combinations will be increased in greater proportion.

The last two columns of the table give the resulting resistances when carbon lamps are used, provided the

* This arrangement has double the current-carrying capacity of the one preceding.

currents passed through are not enough to warm-up the filaments. Should the filaments of the lamps be heated by the current, the resultant resistances will be decreased; and the device can only be used as a regulator, or when approximate values will suffice.

The arrangement can be used in circuits up to any voltage not exceeding that for which the lamps in use are made. The resistances (lamps) are cheap, and can be renewed without difficulty. Numerous ranges can be secured by using lamps of various candle powers and voltages, care being taken that the lamps in any given case are all similar. The resistances are practically non-inductive.

Any number of resistance units or mats r can be coupled

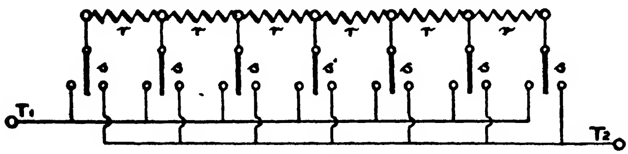


FIG. 169.

up in series in a manner similar to the lamps, and intermediate "tappings" taken to two-way switches s, as in Fig. 169. Such an arrangement gives a large number of combinations, on an extension of the principle just described. The line terminals are T_1 and T_2.

Fig. 170 illustrates a "resistance unit" of a type which is used for numerous purposes in electrical apparatus, and which possesses the advantage that any one or more of the "units" may be removed and replaced by others with the greatest ease.

The resistance, which consists of special wire, is mounted on a split tubular steel core. This core is first coated with a layer of hard enamel, and then with a layer of special composition after the resistance wire has been wound on. The ends of the resistance wire are either secured to terminal lugs or, when the unit is held in spring clip holders, are clamped under terminal screws to which the external circuit may be connected. In such apparatus as *rheostats* or adjustable resistances, etc., a number of units are grouped together, and are generally joined up in series with tappings taken off to a multiple-point switch.

The units are made in various sizes—in order to enable them to be fitted to all sizes and shapes of apparatus. Further, each size is made with different values of resistance and current-carrying capacity. Thus the resistance of a single unit may be anything from ·03ω to 7,000 or 8,000 ohms; and its current capacity from one-tenth to 50 amperes or more. They may be used with alternating as

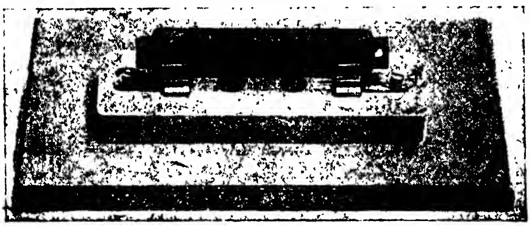


FIG. 170.—RESISTANCE UNIT MOUNTED ON TERMINAL BASE. (*Metropolitan-Vickers.*)

well as direct currents, but they are not quite free from inductance. They are capable of withstanding heat to a considerable degree, so much so that one of the uses to which they may be put is in the construction of electric heaters for moderate temperatures.

Where very gradual change in resistance is required, use is made of the peculiarity that, with separate pieces of carbon in contact, the resistance through them varies very much with the closeness with which the pieces are brought together.

Fig. 171 illustrates a *carbon resistance*, which consists of a number of square carbon plates mounted in an iron frame with an insulating lining of slate. Two metal plates fitted with terminals make contact at either end, while a third plate may be inserted at any intermediate point when it is not desired to include the whole of the carbon plates in circuit. By means of the hand-wheel at the right-hand end of the apparatus, the resistance between the terminals of the contact plates may be varied considerably, the carbon plates being compressed more or less tightly together.

170. CURRENT MEASURING INSTRUMENTS are generally based upon the electro-magnetic effects described in Chap. III, the forces of attraction or repulsion being

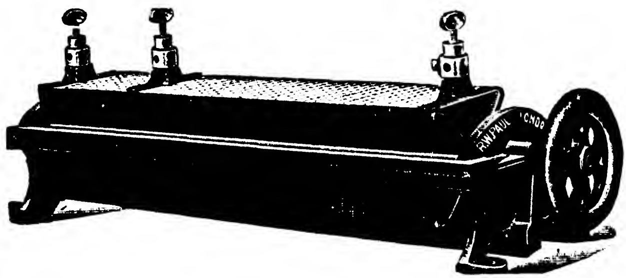


FIG. 171.—CARBON-PLATE RESISTANCE OR RHEOSTAT.

definite and certain, owing to the proportions of the parts and the care taken in design.

A current measuring instrument acts by the magnetic effect of the current upon (*a*) a permanent magnet or magnetic needle, (*b*) a mass of soft iron, (*c*) another movable conductor carrying the same current, or (*d*) an induced (secondary) current created by the current to be measured as a primary current.

One part of the instrument is fixed and another is movable, and the movable part exerts a deflecting force which is balanced by a controlling force. The movable part has fixed rigidly to it an index or pointer. The controlling force tends to bring the pointer back to zero.

The shape of the coils carrying the current varies according to whether the field produced is intended to be uniform, i.e. of equal strength throughout, or non-uniform.

Either of the two parts, the current carrying conductor or the magnet, may move, the other being fixed. This classifies two main divisions—

(*e*) Fixed coil galvanometers or ammeters.
(*f*) Movable coil galvanometers or ammeters.

A galvanometer is an instrument for the measurement of minute or small currents, and an ammeter for larger currents. They, therefore, differ in construction in the same way that a chemical balance differs from a grocer's scales. But they have in common three essentials—

(*g*) Means of creating a deflecting force; (*h*) a controlling or restoring force; and (*i*) a mode of reading the deflection, or deplacement, of the moving part.

The controlling force may be—

(*j*) Magnetic control, as in the tangent galvanometer.
(*k*) Elastic control, as in the Siemens dynamometer, and spring or torsion-controlled instruments.
(*l*) Gravity control, as in the Kelvin Balance, and instruments with weights bringing the pointer back to zero.
(*m*) Inertia control, as in the ballistic galvanometer.

171. CLASSIFICATION OF INSTRUMENTS. The different types are conveniently described under the following heads—

(i) **Moving-magnet Principle** for direct currents only. In instruments of this class the moving element consists of a permanent magnet in the form of a magnetic needle. The deflecting force consists of the lines of force due to the current, and the controlling force may be either gravity, a spring or springs, a permanent magnet, or an electromagnetic field.

(ii) **Moving-coil Principle** for direct currents only. In this class, the moving element of the instrument consists of a light coil of wire, and the fixed portion of a strong permanent magnet. The coil is suspended or pivoted in the field of the magnet and, when a current passes through it, is deflected by the lines of force of the magnet.

The controlling force is usually a coiled-up spring, of the watch-spring form, but for special work and in galvanometers it is the torsion of a wire (unifilar suspension), or the restoring couple of two wires side by side (bifilar suspension).

(iii) Those instruments in which the moving portion consists of an armature of soft iron are termed **moving-iron** instruments, to distinguish them from the moving-magnet type.

(iv) **Hot-wire Principle** for direct and alternating currents. In this class, acting by the thermal expansion of the current-carrying conductor, the indicating needle (or mirror) is connected with a wire which is heated, and which sags, expands, or extends on the passage of a current.

(v) **Electrostatic Principle** for direct and alternating currents. In these instruments, the deflecting force is due to the electrostatic attraction and repulsion (or attraction simply) set up between the static charges on fixed cells and movable vanes. The control may be either gravity, electrostatic, or a spring or torsion of a wire.

As the circuit through such instruments is open, they take no current (except that necessary to provide the charge), and are true voltmeters.

(vi) **Dynamometer Principle** for direct and alternating currents. The action of instruments of this class is due to the phenomena of attraction and repulsion of currents, and spring control is usually employed.

(vii) **Induction Principle** for alternating currents only. The moving portion of instruments of this kind consists of a conducting vane in which alternating currents are induced by the alternating magnetic fields set up by fixed electro-magnets. The interaction which then takes place causes the vane to be moved against the controlling force of gravity, or springs. These instruments act like a.c. motors and coil up a spring until the torque of the motor equals the elastic resistance of the spring.

Typical instruments of the different classes are described after the methods for measuring small currents, resistances, and pressures have been dealt with.

172. CHOICE OF INSTRUMENT. In selecting an instrument to meet certain conditions, the following points, amongst others, have to be considered—

(*n*) *Dead-beatness* or absence of swinging about. A dead-beat instrument is one which quickly takes up its position and returns to zero without repeatedly overshooting the mark, or oscillating backwards and forwards like a pendulum. Such an instrument is damped either by air friction, liquid friction or an eddy current brake.

(*o*) Applicability to *measurements on d.c. and a.c* Some instruments are only useful on d.c., others on a.c., while a third class work more or less satisfactorily on both.

(*p*) *Sensitiveness*, or response to changes in the quantity being measured.

(*q*) *Internal resistance*, the lower the resistance of the coils of a current-measuring instrument, other things being equal, the better.

(*r*) *Zero-keeping qualities*. The pointer should return exactly to zero when current is off.

(*s*) *Range*. That is the proportion between bottom and top readings. Range and accuracy seldom go together.

(*t*) Uniform *open scale* and large divisions. The position of the pointer has to be read by the eye, hence the larger each division is and the more equal they are throughout the scale the more readily the position of the pointer can be ascertained.

(*u*) *Accurate* to standard values. Obviously a measuring instrument should be correct, but this costs money, so there are grades, the dearer class being the more accurate.

(*v*) *Power* taken to operate. Instruments cannot be put into a circuit without slightly altering the conditions, so the less power they take the smaller that alteration.

A direct-reading instrument is one which, when joined in circuit, at once indicates the required value.

Direct-reading instruments are those calibrated, or marked off on the scales to read pressure in volts in the case of voltmeters, amperes in the case of ammeters, and watts in wattmeters. Other instruments require the use of a constant or number by which the divisions on the scale have to be multiplied to get, from the indications of the scale, the quantity measured.

The full scale deflection of an instrument is the movement of its indicating pointer to the top or highest mark on the graduated scale. Most instruments have the zero of the scale to the left and read right across to full scale deflection on the right. A centre-zero instrument is one in which the zero is in the middle of the scale, the graduations being numbered from that point to right and to left. Such instruments are useful when the direction of the current is one of the factors desired, as well as its magnitude.

Current is directly measurable by various forms of galvanometer, provided they have been previously calibrated, and a calibration curve constructed. The latter is a kind of chart which gives the value of the current for any given deflection of the galvanometer needle.

To calibrate an instrument with arbitrary divisions on its scale, currents are sent through it in series with another instrument measuring these currents ; or it is put in circuit with a battery and a number of variable resistances. The comparative values of the currents are then inverse to the total resistance of the circuit in each case. The actual value of the currents can be found by Ohm's law if the e.m.f. and internal resistance of the battery are known.

A scale is of arbitrary divisions when these are, say, in degrees, or the lengths are equal but not necessarily proportional to the currents. The cost entailed in accurate graduation of high-grade instruments is one of the reasons why they are expensive. Mass production enables cheap instruments to be made ; then each scale is not graduated by itself, but one is checked out and the others are merely copies.

173. DETECTORS or *galvanoscopes* are instruments which will detect a direct current, indicate its direction, and show whether it is weaker or stronger than another current. A telephone receiver will act as a partial detector, for it will indicate the presence of current in the circuit if the latter be made and broken while the receiver is connected up. It will not, however, show the direction of a current, or its relative strength. A *galvanometer* is a much more sensitive instrument than a detector ; and will also show how much weaker or stronger one current is than another. The currents that may be sent through sensitive galvanometers are generally very small indeed, something in the neighbourhood of a millionth of an ampere. A *milliammeter* is adapted to measure such small currents as fractions of an ampere, from 0·001 upwards. An *ammeter* may be constructed for large currents, and will indicate directly on its dial the value in amperes of the current passing through it.

There are many different kinds of galvanometer, of which five typical varieties will be briefly explained.

174. THE VERTICAL DETECTOR consists of a vertical magnetic needle mounted on a horizontal spindle

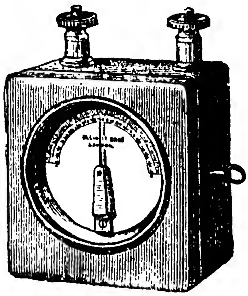


FIG. 172.—ORDINARY DETECTOR. (*Elliott Bros.*)

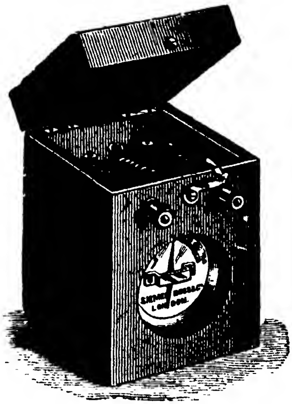


FIG. 173.—DETECTOR AND BATTERY COMBINED. (*Siemens.*)

which carries at one end the blackened brass pointer seen in front of the dial. The needle is surrounded by a coil of wire, the ends of which are joined to the terminals on the top of the case, as in Fig. 172.

Generally, two separate coils of wire are wound on the instrument, one having few turns of comparatively thick wire, and the other many turns of fine wire. The thick-wire turns enable the instrument to detect currents which, if passed through a coil of many turns and therefore of high resistance, would be weakened too much to affect the needle sufficiently, that is, in the case of circuits of low resistance with small e.m.f.'s. On the other hand, the fine-wire coil enables an already weak current to have effect on the needle.

The higher resistance of the fine-wire coil causes little reduction in a circuit already of high resistance, while the small current being taken many times round the needle gives a sufficiently strong field to cause an appreciable movement of the needle.

Only low resistance instruments may be usefully inserted into circuits of low resistance, but those of high resistance may be put into circuits already of high resistance. The reason is that, when a measurement is taken, one must not alter the quantity to be measured. To insert a high resistance instrument into a low resistance circuit would have the result of materially altering the current which was flowing before, and which is the very quantity it is desired to measure.

When the detector has two coils, it is provided with three terminals. The ends of the short or thick-wire coils are usually joined up to terminals 1 and 2, and those of the long or fine-wire coil to terminals 2 and 3 ; terminal 2 being the middle one.

A linesman's detector is invaluable for numerous rough tests for continuity, breaks, short-circuits, etc., and for ascertaining the condition of batteries. It is all the more convenient when its case is made large enough to contain two or three small dry cells, as a separate battery is then unnecessary. Such a combination is shown in Fig. 173.

175. THE HORIZONTAL DETECTOR may be termed either an extra-sensitive detector, or a fairly-sensitive galvanometer. The main differences between it and the vertical detector are that the needle moves in a horizontal plane, and that it turns on a jewelled centre, off which it may be lifted by means of a catch, when not in use. The instrument is wound with a single coil of very fine wire, the ends of which are connected with two terminals mounted on ebonite bushes.

The coil is often wound to a resistance of about 1,000ω, so that it has some thousands of turns of wire on it. Because of this, and the delicacy with which the needle is pivoted, the instrument is sensitive to small currents. In fact, it can be made with a sensitiveness such that one-millionth of an ampere will give a deflection of about 1°. The pointer attached to the needle spindle moves over a mirror, and when taking a reading on the scale, the eye should be in such a position that the pointer exactly covers its reflection

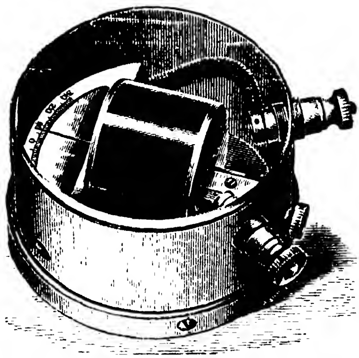


FIG. 174.—HORIZONTAL DETECTOR OR GALVANOMETER.

in the mirror. This prevents *parallax error*, by which is meant a sideways reading of the position of the pointer.

This galvanometer is suitable for ordinary bridge and similar tests, and could also be used in the methods for locating faults on underground mains. When suitably arranged with two windings, it forms a handy *differential galvanometer* of fair accuracy, and can then be used for the tests described later.

A pointer adds weight to the moving part of a galvanometer and necessarily makes the instrument less sensitive, because the greater the weight the stronger the parts must be. Where great sensitiveness is required, a beam of light is thrown on to a mirror attached to the moving part, and the mirror sends a reflected beam on to a scale, the movement of the spot of light on the graduated divisions of the scale being observed.

176. THE REFLECTING GALVANOMETER. One of the numerous forms of the moving magnet class of instruments is illustrated in Fig. 175. Fig. 176 shows, on a larger scale, the movable portion carrying the mirror *M*, by which the beam of light thrown from a lamp is reflected back on to a scale. Thus the very slightest movement of *M*

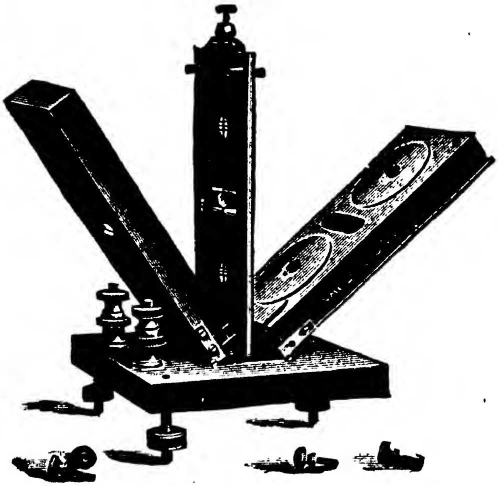


FIG. 175.—REFLECTING OR MIRROR GALVANOMETER WITH COILS OPENED UP.

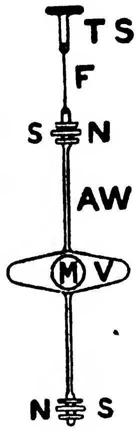


FIG. 176. NEEDLES AND MIRROR OF REFLECTING GALVANOMETER.

results in a perceptible deflection of the spot of light on the scale, which may be 3, 4, or more feet distant from the galvanometer. The reflected beam of light thus acts as a long weightless pointer.

AW is an aluminium wire which carries the two compound magnetic needles **S N**, **N S** (which it will be noticed are *astatically* arranged), the vane **V** of aluminium foil, and the mirror **M**. **A W** hangs from a thumb-screw **T S** by a very fine fibre **F** of cocoon silk.

The top and bottom coils are made in halves, and are mounted on hinged frames; this arrangement rendering the needles, etc., readily accessible for inspection or adjustment. There are thus really four coils, which are connected up in series to the two terminals. The connections of the coils are so made that the direction of the current in the lower coils is opposite to that of the current in the upper coils, so that they combine to deflect the needles in the same direction. The instrument requires careful levelling, in order that the needles and vane may hang quite clear. The three levelling screws enable the instrument to be adjusted, and to rest firmly upon its support. When the instrument is set up, V turns in a small and almost enclosed chamber, so that it "damps" or retards the oscillations of the needles.

Such a galvanometer as this is suited for the bridge and potentiometer tests described later on; and being very sensitive, it is employed in cable factories for "tests at maker's works" of insulation. It provides the most delicate means known of ascertaining the presence and magnitude of an extremely minute electric current. Instruments of this type, but of more elaborate construction, have been made which will give 1 mm. deflection of the spot of light on the scale at a distance of 3 metres with the current produced by 1 volt through 150,000 megohms, the coils of the galvanometer having 140 ohms.

177. THE MOVING-COIL GALVANOMETER acts on the principle that if a coil of wire be suspended or pivoted in a magnetic field and a current be sent through the coil, the latter will tend to move round in the field in a direction depending on the directions of the current and of the field.

The current is taken into and out of the coil by the wire by which it is suspended above and below; or, if the coil is pivoted, by a fine spiral spring above and another below the coil. A pointer fixed to the coil indicates the deflection on a dial, similar to Fig. 174, in the portable type. Moving-coil instruments have superseded all others for ordinary work, owing to their convenience, compactness, uniformity of scale-divisions, and the fact that they do not need to be set in the magnetic meridian ; while the large magnets, which create the field in which the coil moves, do not alter much with time so that the calibration of the instrument is very constant.

Three central-zero pointer instruments of this class on being tested gave the following results—

	Resistance between terminals in ohms.	Current in micro-amperes per div. of scale.	No. of divisions on scale, each side of zero.	Current in micro-amperes for full-scale deflection.	Pressure in milli-volts across terminals for full-scale deflection.
A .	13·7	2·76	30	82·8	1·14
B .	112·0	1·63	45	73·3	8·22
C .	220·0	0·65	50	32·5	7·15

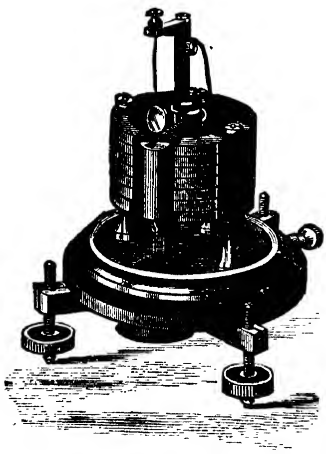


Fig. 177.—Galvanometer with Cover Removed.

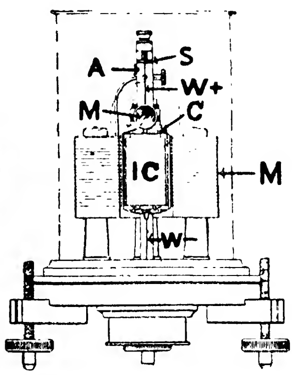


Fig. 178.—Holden-D'Arsonval Galvanometer. (Front Elevation.) (*Pitkin.*)

A typical form of the reflecting type of suspended-coil instrument is the *Holden-D'Arsonval Galvanometer*. A front elevation is given in Fig. 178, a plan in Fig. 179, while the coil and its holder are shown separately in Fig. 180.

M is a circular compound permanent magnet, in the field of which the coil C is slung by means of the flat phosphor-bronze wires W + and W −, these wires serving also to lead the current into and out from the coil. The ends of the wires are held fast by suitable pinching nuts at top and bottom, and the tension may be adjusted by means of the screw S. The coil C, of several turns of fine wire, is wound on a light silver frame F (Fig. 179), which, as it forms a closed circuit of little resistance, tends to damp the oscillations of the coil. Thus, while the coil is moving,

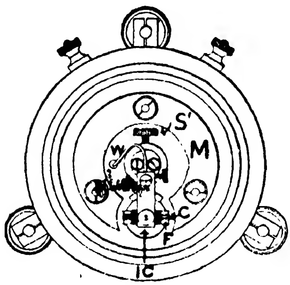


Fig. 179.—Holden-D'Arsonval Galvanometer (Plan).

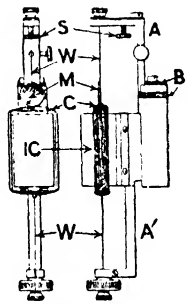


Fig. 180.—Holden-D'Arsonval Galvanometer (Coil Holder).

currents are induced in this frame, and these—in accordance with Lenz's law—tend to stop the motion producing them; but the inductive action—being only momentary—does not affect the ultimate position taken up by the coil. The flat strip or wire suspension tends to keep the coil with its plane parallel with the field, and it is against the torsion of this strip that the coil is deflected. M (Figs. 178 and 180) is the mirror whereby the movements of the coil are shown on a scale. IC is a soft-iron core by which the field of the magnet is concentrated. By loosening the screw S′ (Fig. 179), and releasing the wire W, which is connected with one of the terminals, the frame, core, and coil may be removed bodily from the main portion of the instrument

(Fig. 180). This renders the repair or adjustment of the suspension very easy. The top angle-piece **A**, which supports the upper suspension of the coil, is insulated from the lower portion of the frame by the insulating pieces **B**. **A** is connected by the wire **W** (Fig. 179) with one of the terminals, while the other terminal is in connection with the lower end of the coil through the framework and lower angle piece **A′** (Fig. 180).

To render the galvanometer suitable for various classes of work, it is generally supplied with three or four separate coils (and holders) having different numbers of turns and different resistances.

The shape of the coil varies with different makers, and depends upon whether the galvanometer is intended merely to detect the minutest current, or to measure the magnitude of small currents. In the Crompton design the coil is circular, in others it is rectangular (as in the case described); while in the Ayrton Mather it is compressed sideways, so that the iron core is omitted.

178. LAMP AND SCALE. Fig. 181 shows a form of lamp and transparent scale in which a small incandescent lamp is used from a two-cell secondary battery. The standards supporting the lamp and scale have a sliding vertical adjustment, and are hinged to the weighted base, so that the whole may be folded up to go into a case. The focusing tube, carrying the lamp at one end and a double convex lens at the other, is mounted on a ball joint. The lamp is fixed on an ebonite block carrying two terminals, the block having a bayonet-joint fitting to the focusing tube.

The lens has a fine vertical line etched on it, and this line appears in the centre of the reflected spot of light on the scale, and acts as the index. The ground glass scale may be adjusted horizontally by means of a pinion and rack, which are operated by the thumb-screw seen in the figure.

Transparent scales are used when the lamp and scale are placed between the galvanometer and the observer. When the latter stands between the instruments, a cardboard scale is sufficient. In test rooms it is convenient to use a larger incandescent lamp, and take the current from supply mains—through a resistance if need be.

179. THE TANGENT GALVANOMETER. A knowledge of the principles of this instrument is important to the elementary student, though it is not now used in practical testing. It affords, however, a means of measuring a direct

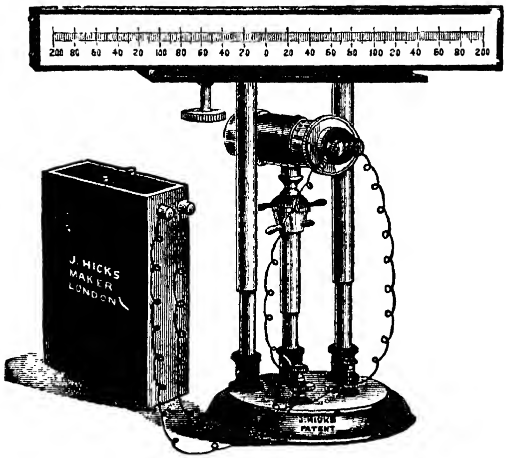


FIG. 181.—SCALE FOR REFLECTING GALVANOMETER.
(*Hicks.*)

current when nothing else is available, as it can be rigged up with a wooden hoop and a pocket compass. Further, it is the simplest illustration of what is meant by "absolute measurement."

Take a circular coil of wire of one or any number of turns, and of a diameter of not less than, say, 8 ins. When the coil is placed vertically and a current is passed through the coil, the field in the centre will be fairly uniform, that is to say, the lines will be straight and parallel with each other. Furthermore, the field will be at right angles with the plane of the coil, or, in other words, the lines of force will run straight through the centre of the coil from face to face. Now if a relatively small magnetic needle (say not more than ¾ in. long) be freely hung or pivoted at the centre of the coil, however much it turns it will be wholly in a uniform field, which will therefore exert a force in one constant direction upon it, the amount depending on the strength of the current.

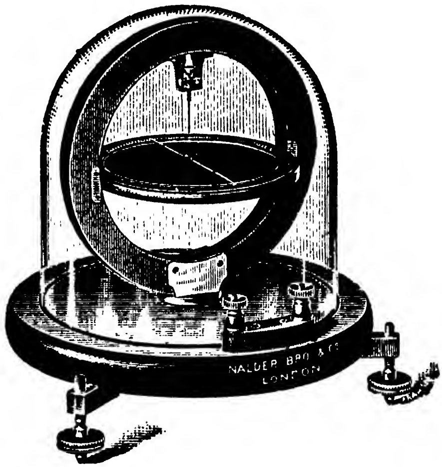


FIG. 182.—TANGENT GALVANOMETER.

Fig. 182 illustrates a simple form of tangent galvanometer, and the coil, needle, and pointer can be clearly seen. The needle is hung upon a fine silk thread, which in reality is much finer than would seem from the illustration. If a large *controlling magnet*, such as a permanent bar magnet, be placed beneath the base of the instrument so that its field is at right angles with the field of the current in the coil, it will exert a constant unidirectional force upon the needle; or instead of a controlling magnet, the Earth's force alone may be allowed to act on the needle, in which case the galvanometer coil must be put with its plane in the magnetic meridian. In the latter case, however, although the galvanometer would be more sensitive, the needle would take longer to come to zero after deflection.

When a magnetic needle, free to turn about a centre in a horizontal plane, is acted upon by two horizontal forces at right angles with each other, it will take up an intermediate position between the two directions. If acted upon by the *controlling force* alone (the controlling magnet's or Earth's field), it will point in the direction of that force, and this will be its zero position. When the current's *deflecting force* acts, the needle will move round over a certain number of degrees, and come to rest at a certain deflection δ (Greek letter *delta*). The ratio of the deflecting force to the controlling force is—

$$\text{deflecting force} = \text{controlling force} \times \tan \delta$$

$$\text{or} \frac{2 \pi C n}{r} = H \times \tan \delta$$

$$\text{That is, current (in c.g.s. units)} = \frac{Hr \tan \delta}{2 \pi n}$$

Where δ = deflection of needle, in degrees.
r = radius of coil, in cms.
n = no. of turns in coil.
H = strength of controlling field, in dynes.

As these values alone would give the current in c.g.s. units, they are multiplied by 10, to bring C to amperes. Tan δ signifies the tangent of the angular deflection δ, and its value is procurable from a table of tangents (see end of Vol. II).

With any given tangent galvanometer, the value $\frac{r}{2 \pi n}$ is a constant; and so also is $\frac{Hr}{2 \pi n}$ for any given series of tests. Thus the comparative strengths of, say, two currents are then as the tangents of their angles of deflection. Thus, supposing one current C produces a deflection of 39°, and another C' a deflection of 27°; their comparative strengths are not as 39° is to 27°, but as tan 39° is to tan 27°, or—

$$C : C' :: \tan 39° : 27°$$
$$:: 0{\cdot}810 : 0{\cdot}509$$
$$\text{i.e. } C = \frac{0{\cdot}810}{0{\cdot}509} C' = 1{\cdot}59\, C'$$

If two cells, acting in the same direction, are joined in series through a tangent galvanometer, the total resistance of the circuit being R, the current $C_1 = E_1 + E_2/R$. If the cells are then joined in opposition, the current $C_2 = E_1 - E_2/R$, and $E_1 : E_2 :: C_1 + C_2 : C_1 - C_2$.

180. SHUNTS. The *sensitiveness* of a galvanometer is proportional to the amount of movement of its pointer produced by a given current; thus the larger the deflection the greater the sensitiveness. The sensitiveness depends upon the design and details of construction of the instrument. It also depends upon the strength of the controlling force; so that decreasing the latter increases the sensitiveness. For measurements with very small currents it is necessary to employ a galvanometer having great sensitiveness. In dealing with comparatively large currents, if we use a galvanometer of too great sensitiveness, the moving part will be deflected beyond the end of its usual range. In such a case there will be considerable risk of damage to the instrument. To obtain useful readings the pointer must come within the graduated scale. When it is desired to reduce the sensitiveness of a galvanometer, the usual method is by making use of a *shunt*. This is simply a conducting by-path, or parallel circuit, which is connected across the terminals of the galvanometer, and which allows only a fraction of the main current to pass through the instrument. A shunt reduces the potential difference across the terminals of the instrument shunted. The usual provisions for shunting a galvanometer are shown in Fig. 183. Here **P** is a plug-board, which is so arranged that any one of the three resistances or shunts **S, S, S** can be connected across the galvanometer terminals by inserting a contact plug in one or other of the three sockets.

The relations between the currents in the shunt and galvanometer circuits and that in the main circuit may be determined as follows—

Let C = the main current.
Cg = the current in the galvanometer.
Cs = the current in the shunt.
G = the resistance of the galvanometer.
S = the resistance of the shunt.
V = the voltage-drop across the terminals of the galvanometer

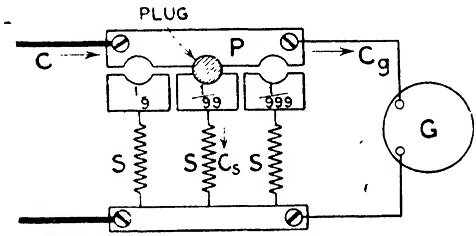


FIG. 183.—GALVANOMETER SHUNTS.

By Ohm's law we know that—

$$V = Cg \times G \text{ and } = Cs \times S.$$

Now the combined resistance of the divided circuit is—

$$\frac{1}{\frac{1}{G} + \frac{1}{S}} = \frac{G \times S}{G + S}$$

Hence— V also $= \dfrac{G \times S}{G + S} \times C$

Then— $Cg \times G = \dfrac{G \times S}{G + S} \times C \quad \therefore Cg = \dfrac{S}{G + S} \times C$

Similarly— $Cs = \frac{G}{G + S} \times C$

and $C = \frac{G + S}{S} \times Cg$

From the above equations, it will be clear that the resistance of the shunt circuit may be so adjusted that any desired fraction of the main current may be left to pass through the galvanometer.

Suppose $\frac{1}{n}$ th part of the main current is to traverse the galvanometer circuit— $Cg = \frac{1}{n} C$

While n must $= \frac{G + S}{S}$

i.e.— $n \times S = G + S$

$\therefore\ n S - S = G$ and— $S = \frac{G}{n - 1}$

n is called the *multiplying power of the shunt.* The *multiplying power* is the ratio between the main current and that in the galvanometer circuit; or the ratio between the deflection that would be indicated by the needle if the whole current passed through the galvanometer, and the deflection given when the shunt is in use The *equivalent deflection* is the actual deflection $\times$ n.

The p.d. across the shunt V is $Cg \times G$, and the current Cs through it is $C - Cg$, hence the resistance of the shunt S must be $\frac{Cg \times G}{C - Cg}$

When n = 10 then $S = \frac{1}{9} G$

,, n = 100 ,, $S = \frac{1}{99} G$

,, n = 1000 ,, $S = \frac{1}{999} G$

In these three cases, the sensitiveness of the galvanometer would be reduced by the shunts to $\frac{1}{10}$th, $\frac{1}{100}$th, and $\frac{1}{1000}$th respectively ; and these are the usual values, as indicated in Fig. 183. Other values conveniently used are $\frac{1}{3}$, $\frac{1}{10}$, $\frac{1}{30}$, $\frac{1}{100}$, $\frac{1}{300}$ and $\frac{1}{1000}$. In order that the ratio between the resistances G and S may remain constant, the shunt wire should be of some material having the same *temperature coefficient* as the galvanometer circuit.

A shunt is only of use when the resistance of the circuit outside the galvanometer and its shunt is considerable. If an instrument **G** in Fig. 184 be placed across the terminals of a battery **B**, to add a shunt, **S**, merely gives a second conducting path without altering the current through the

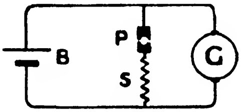


Fig. 184.

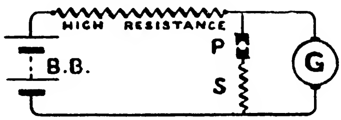


Fig. 185

instrument. Shunts are used generally where the resistance already in circuit is so high relatively to the instrument to be shunted that the main current is not very different whether the shunt be connected or not, as in Fig. 185, where the many-celled battery **BB** maintains the same current through **HR** as in the previous case.

The joint resistance of the galvanometer and shunt will be less than the resistance of the galvanometer alone, so that the total resistance of the circuit, even if high, will be reduced to some extent and the main current correspondingly increased. The proportion of the galvo current to main current will always be $S/G + S$, but the main current will not be quite the same before and after the insertion of the shunt. This explains a difficulty sometimes met by beginners when taking tests, who are puzzled to find a shunt giving different results to those anticipated.

Any instrument for measuring direct current can have its range extended by the use of a shunt. Thus an ammeter to indicate 1 amp., might be used for 10 amps., by shunting it with nine-tenths of its own resistance, as then 9 amps. would pass through the shunt and 1 amp. be indicated on the instrument. Shunts cannot be used with most alternating current instruments in this way, because the simple form of Ohm's law does not apply.

181. CONSTANT CURRENT SHUNTS are used where it is important that the main currents should not be altered by shunting an instrument in the circuit. The resistance of a shunted instrument is $\frac{G \times S}{G + S}$, instead of G when it was unshunted. If when placing **S** across the terminals we at the same time insert another resistance $= G - \frac{G \times S}{G + S}$

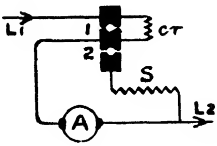


FIG. 186.

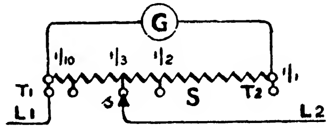


FIG. 187.

in series, the total resistance is reproduced, and the main current is unaltered. In Fig. 186 **A** is an ammeter with a plug switch enabling a shunt **S** to be placed across its terminals. With the plug in 1 the compensating resistance *c r* is cut out. Plugging in 2, the instrument is shunted, but the compensating resistance is brought into circuit and the resistance of the circuit remains unaffected.

A **universal shunt** is one which can be used with any galvanometer. In Fig. 187 the **G** is joined up to T_1 and T_2, the ends of a resistance, which is usually (but not necessarily) about ten times the resistance of **G**. One of the leads comes in to T_1, the other is taken to a slider *s*, which can make contact with the shunt **S** at fractional points where tappings are taken off. If from T_1 to *s* be one-third of the total then the multiplying power is 3, compared with conditions when L_2 is joined to T_2; this position being accordingly marked 1/1. The universal shunt is not strictly a constant-total-current shunt, although it approaches this. It can be used with any galvanometer, irrespective of resistance, so far as its multiplying power is concerned. Thus it is gradually supplanting the older form for ordinary work.

182. SPLIT-COILS. Two ranges can be got without shunts in the case of an ammeter, if the whole current passes through a deflecting coil or coils in the instrument. Instead of one coil carrying the whole current its place is taken by two coils, each of which will carry half the current. For the maximum range these two coils are put in parallel,

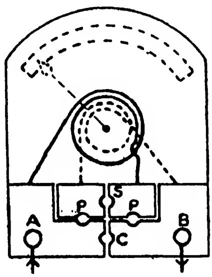


FIG. 188.

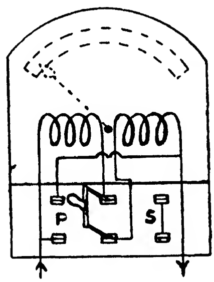


FIG. 189.

one coil shunting the other, and the current divides equally between them, giving the same effect as a single coil would have done.

For a current smaller than half the maximum the two coils are put in series, so that half the current with twice the turns gives the same effect on the moving part, and a full scale deflection is obtained with half the maximum current. This device is found on the current coils of several types of wattmeter, two methods of achieving the result being indicated in Figs. 188 and 189. It is also a useful mode of winding stator coils on single-phase a.c. motors, which may at one time be wanted for, say, 200, and at another for 400 volts.

In Fig. 188 **A** and **B** are the line terminals. If a plug be inserted between these blocks at **C** the instrument is short-circuited. If the plug is placed at **S** the two coils are in series. If plugs be inserted at **P** and **P**, the coils are in parallel, and n = 2. In Fig. 189 the coils are drawn in a different form and a double-throw or change-over switch is shown. If this be thrown to the left at **P** the coils are paralleled, and if to the right at **S** the coils are joined in series.

183. VOLTMETERS. If an instrument, capable of measuring very small currents, be placed in series with a very high resistance, as in Fig. 185, the current through the circuit in which it is connected will be proportional to the e.m.f. in that circuit. As the current is extremely small its indications will not be appreciably affected by the resistance of the source of e.m.f., or of the connecting leads. Such a combination, with a suitably graduated scale, is termed an *indicating voltmeter*. Pressure and its variation may be recorded by a *recording voltmeter*.

Electrical pressure is generally measured by instruments which are connected to the two points of a circuit, between which it is desired to measure the p.d. or pressure. A voltmeter must always have a comparatively high resistance, in order that the total resistance (and consequently the p.d.) between the points of the circuit tested may not be appreciably altered.

An ordinary voltmeter is connected directly across the circuit, as indicated at **A A′** in Fig. 190. Very often an extra resistance **R** is connected in series with the actuating coil of the voltmeter **V**, this being generally fitted inside the case. The very small current passing through the instrument is proportional to the p.d. in volts between its terminals, including the extra resistance **R**, and its dial is graduated accordingly. **A** shows the voltmeter connected between the mains running, say, from a generating station to a distributing network.

In practice, a d.c. voltmeter comprises a milli-ammeter in series with an external or series or swamping fixed high resistance of thousands of ohms, if intended to measure hundreds of volts. The winding which is usually given to an instrument of the permanent magnet moving coil type is such that its pointer goes to the top of the scale, or gives full-scale deflection, with about 15 milli-amperes through it. The external resistance cuts down the current to this value, so that a 200-volt voltmeter would have twice the resistance of one for 100 volts, the indicating portion being the same in both.

A **milli-voltmeter** is a low-reading instrument indicating in thousandths of volts The three instruments

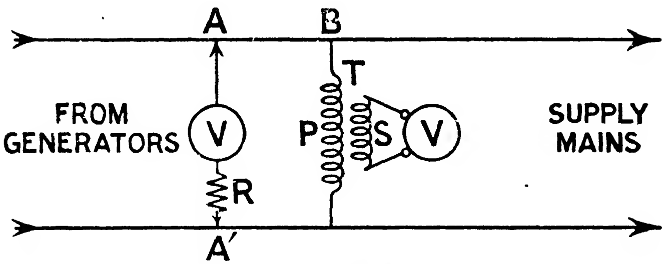


FIG. 190.—CONNECTION OF VOLTMETERS ACROSS A CIRCUIT.

in § 177 could be used as d.c. milli-voltmeters for the maximum pressures shown in the right-hand column of the table.

Either direct or alternating-current voltmeters may be joined up as above described ; but—in the latter case—another method is available, which is especially suitable for high-pressure circuits, as the direct connection of the voltmeter to the circuit is avoided. This is shown at **B** in Fig. 190. Here **T** is a *potential transformer*, which consists of an iron core wound with two separate coils of wire **P** and **S** ; the alternating current in **P** inducing a secondary current in **S**, as described in Chap. XVI. The pressure at the terminals of **S** is less than that at the terminals of **P**, according to the difference in the number of turns ; but the voltmeter scale may be so marked as to indicate the actual pressure on **P**.

184. MULTIPLIERS. Voltmeters are supplied—when required—with *multipliers* of various values. For instruments of the classes which take a current to operate them, these consist of resistance coils mounted in boxes, and having such values as to increase the indications of the voltmeter by stated amounts. The principle is as follows. If a voltmeter be connected in series with a resistance which will reduce any given *previous* deflection (obtained without the resistance) to $\frac{1}{2}$, $\frac{1}{5}$, $\frac{1}{10}$, etc. : then when the resistance is in circuit, the real values of the deflections obtained are got by multiplying them by 2, 5, 10, etc., as the case may be.

Just as ammeters are inserted in a circuit, and their range may be extended by the use of shunts, so voltmeters, which are coupled across a circuit, may have their range extended by the use of multipliers.

If two voltmeters are coupled in series across a circuit, the p.d. between the points to which they are connected will divide in direct proportion to their resistances. The same thing will happen if one of the resistances be a coil of wire wound in a box instead of a voltmeter coil.

Ex. (*a*). If a pressure of about 440 volts had to be measured, and the only voltmeters at hand were one for 220 volts and of 2,000 ω, and another for 250 volts and of 2,400 ω, by coupling them in series across the line they would read—

$$\frac{2000}{2000 + 2400} \times 440 = 200 \text{ volts}$$

$$\text{and} \quad \frac{2400}{2000 + 2400} \times 440 = 240 \quad ,,$$

giving an aggregate reading of 440 ,,

To further extend the range of a voltmeter of the moving-coil type, if sufficient high resistances were not obtainable, the multiplying resistance could be put in series with the voltmeter, and a shunt placed across the terminals of the voltmeter.

Ex. (*b*). A voltmeter reading up to 30 v. and taking 15 m.a. for full scale deflection could measure 450 v. by having 7 resistan es equal to its own in series with it, and another of the same resistance in shunt with it, as in Fig. 191. The res. of **V** = 30/0·015 = 2,000 ω, so that the circuit from l_1 to l_2 would have a res. of (7 × 2000) + (2000/2) = 15,000 ω, and would allow 450/15000 = 0·03 amp. or 30 m.a. to flow. Of this half would go through **V**, causing a full scale deflection of 30 v. and the other half through **S**. The multiplying power would be 450/30 = 15.

A "volt-box," or *potential divider*, is a high resistance coupled across a circuit with tappings, or connections, to intermediate points. Suppose, with an electrostatic voltmeter of 100 volts, one wanted to measure 400 volts. By placing 10,000 ohms across the 400 volts, and connecting the voltmeter across a quarter of the whole, or 2,500 volts, it would be used as a 400 volt instrument, its indications being multiplied by 4 to get the circuit pressure.

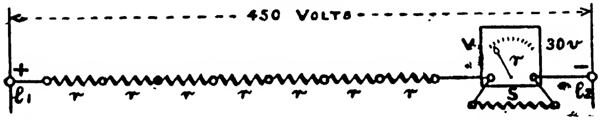


FIG. 191.—VOLTMETER WITH MULTIPLIER AND SHUNT.

Fig. 192 shows such an instrument fitted with a multiplier for altering its range. The connections of this are arranged on the potentiometric principle, the resistances being connected across the terminals **C C**, of the circuit whose voltage is required. The lower **C** terminal and lower **V** terminal are joined together and to one end of the voltmeter, the other end going to the switch lever. When the switch is on contact 1, the circuit voltage is as indicated on the instrument, the multiplying power being 1. When the switch is on the contacts 2, 4 or 5, the circuit pressure is respectively twice, four times, or five times the value of the voltmeter reading.

An **electrostatic voltmeter** has been shown to direct attention to the fact that a potential divider divides the pressure accurately in the above way only when no current is drawn off at the points tapped for the fraction required. That is to say, the arrangement is of use principally with (*a*) balance of p.d.'s, as in the case of the potentiometer, and (*b*) with electrostatic instruments as just described. An electrostatic instrument cannot have its range extended by the use of multiplying resistances placed in series with it as its resistance is practically infinite. It could, however, have its range extended by adding like to like, i.e. putting in series with it condensers, each equal to the capacity of the instrument, or multiples of that capacity.

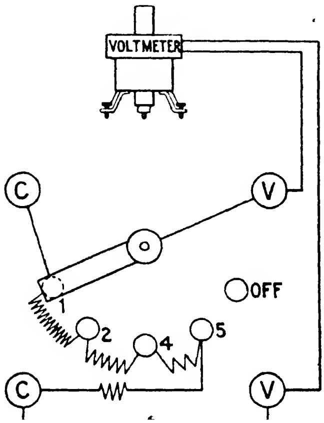


FIG. 192.—CONNECTIONS OF VOLT-BOX AND VOLTMETER.

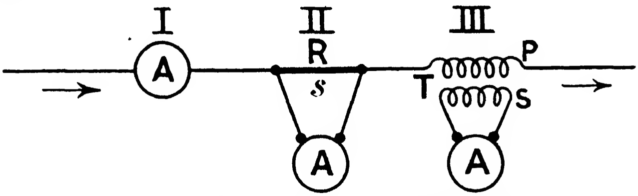
185. AMMETERS. In many cases, instruments acting on the same principle may be used either as voltmeters or ammeters, their scales being differently marked, of course. In such cases, the only difference is that for a voltmeter the coil is composed of a long length of fine wire, whereas in an ammeter a shorter length of comparatively thick wire is employed.

The long length of fine wire has many turns, N, carrying a very small current, c, the short length of few turns, n, carries a large current C. For full scale deflection in either case the product of current by turns is a fixed quantity, i.e. the ampere-turns is the same, or $c \times N = C \times n$.

Strictly speaking, all voltmeters which allow a current of electricity to pass through a closed circuit between their terminals are also ammeters, for they measure a current which is proportional to the volts pressure between their terminals. Such currents are, of course, minute, usually some small fraction of an ampere. Ammeters which are to be connected directly in circuit must necessarily have a very low internal resistance, otherwise their introduction into the circuit would reduce the current it was desired to measure, and there would be a considerable loss of power.

The ordinary method of connecting an ammeter in circuit is shown at **I** in Fig. 193. In this case the main current flows through the ammeter.

186. SHUNTED AMMETERS. When large direct currents have to be dealt with, ammeters are generally joined up as a shunt to a fixed low resistance inserted in the main circuit. In Fig. 193 **II**, a short strip *s* (or a number of strips in parallel) of resistance *R* is inserted in the circuit; and the ammeter is connected (in shunt thereto) to special terminals at the extremities. The current passing through the instrument is then only a fraction of the main current, but the scale is calibrated to give the actual main current value.



I. Adaptable to either d.c. or a.c. instruments.
II. For d.c. work only.
III. For a.c. work only.

FIG. 193. CONNECTION OF AMMETERS IN A CIRCUIT.

The ammeter is wound with fine wire like a voltmeter. The shunt *s*, which may be 3 or 4 ins. long, is made of an alloy which has greater resistance than copper, and whose resistance does not change with moderate changes of temperature. Further, it must be substantial enough to carry the main current without overheating.

It will be evident that the p.d. between the extremities of *s* will be directly proportional to the current passing along the line, as indicated by the arrows.

Thus, **A** will indicate pressures proportional to the currents in the main circuit; so that if, for instance, we had ascertained that 500 amps. gave a deflection of, say, 0·025 volt, we should know that when, say, 0·075 volts is indicated, the current will be 1,500 amps. It is obviously more convenient to graduate and mark the dial of the instrument with the number of amps. proportional to the various p.d.'s across *s* ; and this is exactly how a shunted ammeter is graduated. The winding which is usually given to such an instrument gives full scale deflection with 75 milli-volts between its terminals, if of the moving coil type.

Fig. 194 illustrates a group of shunts of various sizes, the main conductors being bolted thereto through the holes in the side blocks, and the ammeter leads soldered to the small metal tags on the top. The p.d. at these points will

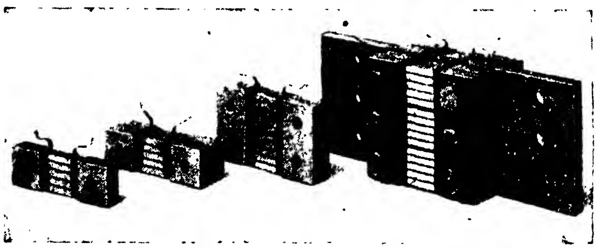


Fig. 194.—Ammeter Shunts.
(*Evershed & Vignoles.*)

depend exactly on the current that is flowing, and the ammeter in this case is really a voltmeter with a fine-wire coil, but with its scale graduated in amperes. In medium-current ammeters, the strip *s*, or *ammeter shunt* as it is usually called, is often fitted in the case of the ammeter.

If the currents in different circuits have to be measured, then separate shunts may be inserted in these respectively, and one indicating instrument **A** can be connected across each of them in turn. The switch used to make the change must be substantial so as to have a very low resistance, as any variation in the resistance of the circuit between the shunts and **A** will introduce errors in the indications of **A**.

Moving-coil or hot-wire ammeters, must of necessity be constructed with fine wire, and (except for very small currents) must therefore be connected up to a shunt as explained above. As hot-wire instruments have practically no inductance they are reliable in a.c. circuits even if shunted.

In **III**, Fig. 193, a purely alternating-current method of connection is illustrated; which, like that shown at *B* in Fig. 190, is specially useful where high-pressure circuits have to be dealt with. Referring to Fig. 193, **T** is a current transformer with a low-resistance primary coil **P** connected in the main circuit, and a secondary coil **S** to which the ammeter **A** is joined up. The main current in **P** induces a secondary current in **S**, and the scale of the ammeter is so marked as to indicate the value of the main current in **P**. By using different current transformers, the same indicator may be employed to measure widely varying main currents.

Where shunts or current transformers are used, the scales of the ammeters must be calibrated or graduated with the instruments connected to the particular leads with which they will afterwards be used, otherwise a change in the resistance in the circuit of the indicating instrument will cause its readings to be incorrect. The resistance of a voltmeter is so high that any resistance likely to be introduced in the leads to it does not make any appreciable difference in the indications it gives.

While there is no objection to removing **A** in **II** Fig. 193, and leaving *s* in circuit, if the ammeter has to be removed for repairs, there are grave objections to removing **A** in **III** unless the terminals of **S** be first short-circuited.

187. TESTS of resistances, currents, pressures, power and energy have to be made in everyday work. Resistances are of various kinds, extending from very low ones as, for example, that of the windings of an armature wound with heavy copper bars, to very high values such as the insulation resistance of a short length of extra-high-tension cable. The methods employed are numerous for that reason and the student should be acquainted with the underlying principles of all the simpler ones while he should realize why one is suitable in a particular case and not in another. One can no more utilize the same apparatus in all cases than it would be reasonable to expect to weigh a human hair and a ton of coal with the same appliance. To illustrate this, it may be mentioned that there are two books concerned with nothing else than the measurement of resistance.* Yet most of what is to be found in these is but an extension or elaboration of points which are given in outline in this volume.

188. RESISTANCE MEASUREMENT. Most of the methods of measuring resistance are indirect; but the ohmmeter and megger are direct-reading instruments.

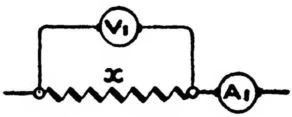


Fig. 195.

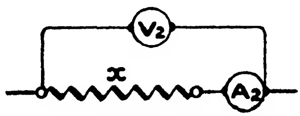


Fig. 196.

If an accurate ammeter A, and an accurate voltmeter V, are available, the simplest method of measuring a resistance is to pass a current through it and take the p.d. which exists across its ends. Then the ratio $\frac{\text{volts}}{\text{amperes}} = \text{ohms}$. In Fig. 195 x is connected by wires to a source of current which can be regulated to give readings on the instruments somewhere in the upper parts of their scales.

Then, if the reading of V_1 were $7\frac{1}{2}$ volts, and the current through A_1 were 25 amps., x would be $7{\cdot}5 \div 25$ or $0{\cdot}3$ ohm.

The current should be as large as can be passed through the resistance without perceptibly heating it, if the cold resistance be wanted; or the normal working current, if its hot resistance is the figure desired. As low reading voltmeters are most readily obtained for direct currents it follows that, if the resistance be low, they should be used.

* *The Measurement of Electrical Resistance*, W. A. Price (Oxford Univ. Press), 6s.; *Methods of Measuring Electrical Resistance*, E. F. Northrup (McGraw Hill), 22s. 6d.

The method is not one of great accuracy because the deflection of each instrument has to be read, and any error in the reading or in the calibration of either instrument produces inaccuracy in the result.

The ammeter must not introduce any appreciable resistance into the circuit, and the voltmeter must not take any appreciable current, if the best results are required. For ordinary commercial work the method is quick and convenient, and is one of those generally employed.

Ammeters have some resistance, and wire-wound voltmeters take some current. If connected up as in Fig. 195, the current taken by the voltmeter V_1/r is measured by the ammeter, tending to give too low a result for E/C. If connected up as in Fig. 196, the pressure-drop in the ammeter $V_2 - V_1$ is measured by the voltmeter, tending to give too high a result. These errors are least when the voltmeter measures the p.d. across x and **A** if the current be small; and when the voltmeter is directly across x only if the current be large.

Let V_1 = Voltage reading in Fig. 195.
C_1 = Current ,, ,, Fig. 195.
V_2 = Voltage ,, ,, Fig. 196.
C_2 = Current ,, ,, Fig. 196.
r = resistance of Voltmeter **V**.

Then if these four readings be taken—

$$x = \frac{V_2}{C_2} - \left(\frac{V_2 - V_1}{C_1}\right) = \frac{V_1}{A_1 - \frac{V_1}{r}}$$

Ex. A voltmeter of 2,000 ω and an ammeter of 0·2 ω were used to measure three resistances, respectively 400, 40, and 4 ω, the supply pressure being 100 volts. The results found were—

Ohms.	V_1	C_1	V_1/C_1	% error	V_2	C_2	V_2/C_2	% error
400	99·95	·299	333·3	− 16·7	100	·249	400·2	+ ·05
40	99·49	2·537	39·22	− 1·96	100	2·488	40·2	+ ·5
4	95·23	23·86	3·99	− ·20	100	23·81	4·2	+ 5·0

189. THE OHMMETER is a two-coil instrument acting as a combination of a voltmeter and ammeter and giving $E \div C$ directly by one reading. An ohmmeter indicates the ratio between the p.d. at the ends of a conductor and the current passing through that conductor, and thus gives the resistance in ohms. An ohmmeter is joined up direct

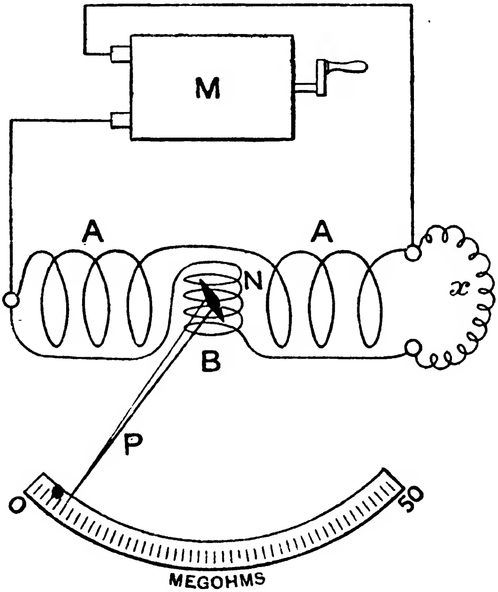


FIG. 197.—DIAGRAM OF ORIGINAL FORM OF EVERSHED OHMMETER.

to the circuit, in conjunction with a permanent magnet hand dynamo (or "generator") giving a suitable e.m.f. for the purpose to which it is intended.

Fig. 197 illustrates the principle of the instrument. Two fixed coils A, A are joined up in series, and between them is fixed a third coil B, with its axis at right angles to the common axis of the other two coils. The fixed coils consist of many turns of fine wire. This circuit is termed the "pressure circuit," and is connected across the terminals of the generator **A**, **A**, thus acting as voltmeter coils. **B**, which is termed the "current coil," is of comparatively low resistance, and carries whatever current passes through the resistance being measured. Inside **B** is pivoted a soft-iron needle **N** carrying the pointer **P**.

Were the needle **N** acted upon by the coils **A**, **A** alone, it would place itself with its length in line with the axis of these coils; while if the coil **B** alone acted upon it, it would take up a position at right angles with the axis of **A**, **A**, i.e. along the axis of **B**. Any piece of magnetizable metal, free to move, will set itself with its greatest length parallel with the lines of any magnetic field in which it is placed. When both coils act together, the needle takes up an intermediate position which depends upon the *resultant effect* of the two fields of **A**, **A** and **B**; and which is consequently proportional to the ratio between the strengths of these fields.

x is the unknown resistance. If this be very great, very little or no current will pass through the coil **B**; while that through the coils **A**, **A** will keep **N** in such a position that **P** is at the right-hand end of the scale. If x be decreased, the current through **B** will increase and the pointer **P** will move back over the scale to such a position that the needle is in equilibrium under the forces exerted by the coils **A A** and **B**. The force due to **A**, **A** may be considered as the controlling force, and that due to **B** as the deflecting force. **M** is the magneto-generator which furnishes the testing current.

All that is necessary in making the test is to turn the handle of the generator at a fair speed, whereupon the pointer of the instrument will at once move to the number of ohms representing the unknown resistance. In measuring a high resistance by instruments of this class, the indications are unaffected by any variations of the pressure supplied by the generator; so that irregularities in turning the handle do not matter, provided the pressure generated be kept high enough to afford a reliable test. The reason for this is, that the current in both circuits will vary with the e.m.f. of M without affecting their proportion.

If the e.m.f. used for testing be fixed, **any Ammeter can be calibrated** as an ohmmeter, since current varies inversely with resistance. Then the scale reads from INF., or open circuit downwards to the lowest resistance, corresponding to the maximum current the instrument will carry.

190. THE DIFFERENTIAL GALVANOMETER. If two resistances are connected in parallel across the same p.d. and the currents are the same through each, the resistances must be equal. If the resistances are not equal, the currents through them will be in inverse proportion to their resistances. Therefore, if in Fig. 198 the current A_1 through r, a standard resistance of known value, be measured on A_1 and A_2 that through x, the unknown resistance, on A_2, then—

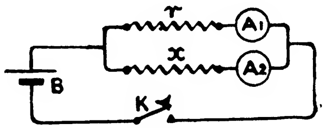


FIG. 198.

Reading on A_1 : Reading on A_2 : : $x : r$,

$$\text{or } x = \frac{A_1}{A_2} r$$

The accuracy of the result depends upon the correctness with which the respective currents can be measured. The use of two ammeters enables the test to be taken by *simultaneous* readings, thus avoiding the error due to any change in the p.d. across r and x due to an alteration in the e.m.f. of B. It is not necessary to use two ammeters if a differential ammeter or galvanometer, i.e. one with two separate windings of equal resistance and equal magnetic effect on the needle, which has two wires wound on side by side on the coil, is available.

In Fig. 199 R and x are connected in parallel across the battery B as in the last figure, although the lay-out or form of the diagram is slightly modified for the sake of appearance, and the currents formerly measured separately by

A_1 and A_2 are now both measured by the one **differential galvanometer G**. With such an instrument, a current in one winding will not affect the needle if at the same time a current of equal value is passing through the other coil in the *opposite* direction. To enable the currents to be made of equal value R in this case must be an adjustable known resistance.

Depress the key and adjust R until no deflection is obtained on the galvanometer. Call one of the galvanometer coils c, and the other c^1. Then as the two circuits c, R

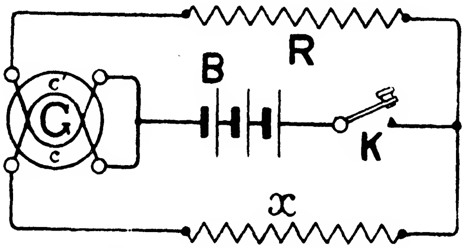


FIG. 199.—MEASUREMENT BY THE DIFFERENTIAL GALVANOMETER.

and c^1, x, have a common e.m.f. due to B; and as equal currents are flowing round both circuits (as indicated by the non-deflection of the galvanometer needle), it follows that the resistances of the two circuits must be equal. The internal resistance of B, being common to both circuits, may be neglected.

$$\text{Then since } c + R = c^1 + x$$

$$\text{and, as } c = c^1, \therefore x = R.$$

This method of measuring resistance requires a special galvanometer. It should be noted, as it leads up to instruments of the two-coil ohmmeter type.

In any of these methods, if the galvanometer be too sensitive, or the ammeter be too small, it can be shunted. Then the " equivalent deflection " is taken as the reading. Thus if, with a differential galvanometer, one coil is shunted and the other not, the resistances will be in inverse proportion to the currents flowing in the two circuits. If coil c^1 be shunted with n = 10 then $x = \frac{1}{10}$th of R.

If the two coils of a differential galvanometer are joined up in series so that the current flows in the same direction through each, the effects of the current on the needle are added. If they are joined up in parallel so that the current splits between them, but both currents going through in the same direction, the effects are added but the deflection will be only half what it was in the previous case. This is illustrative of the double winding of current coils of ammeters and wattmeters mentioned in § 182.

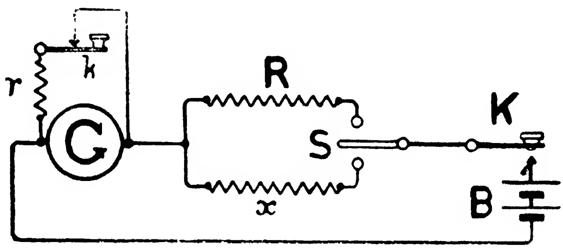


FIG. 200.—MEASUREMENT OF RESISTANCE BY SUBSTITUTION.

191. THE SUBSTITUTION METHOD. Instead of measuring simultaneously the currents through R and x, as in Fig. 198, if only one ammeter or galvanometer is available, they may be measured *successively*, i.e. first one and then the other. Provided that the e.m.f. in the circuit does not change in the meantime there is no error introduced, even if when R is in circuit x is disconnected.

If the galvanometer does not give deflections proportional to the current through it, the **reproduced-deflection** method may be used. In Fig. 200 G is a fairly sensitive galvanometer, R a resistance box, x the resistance to be measured, S a two-way switch, K a key, B a constant battery of a few cells, and r an adjustable resistance shunting the galvanometer by means of which the sensibility of the latter may be varied. This shunt r may be cut out by depressing the top contact key *k*, which is provided with a catch for holding it down when required.

Place the switch **S** so as to include the unknown resistance x in circuit. Alter the value of the shunt r until a convenient deflection of **G** is obtained when **K** is depressed. If x be small and the current flowing round the circuit consequently great, r must be small, otherwise too much current will go through the galvanometer, and its needle move too far. On the other hand, if x have a high resistance, the current will be proportionally small, and it will be necessary to increase r so as not to shunt too much current from the galvanometer, or to cut it out altogether by means of the key *k*. When r is adjusted, note the deflection on **G**. Now put **R** in circuit by means of **S**, and alter its value until the same deflection (as with x) is obtained on **G** without altering r or touching *k*.

$$\text{Then—} \quad x = R.$$

r and R may be boxes of resistance coils of various values, but as it is not necessary to know the value of r, any convenient adjustable resistance will do there.

If the galvanometer has been calibrated, or gives deflections proportional to the currents through it, the **direct-deflection method** is a convenient one. As the object is merely to compare resistances, it is unnecessary to bother about actual current values if the proportion between two currents, one through the known and the other through the unknown resistance, is sufficient to enable the latter to be calculated.

Suppose x to be a high resistance. Then a value of **R** would be selected, say 10,000ω or a megohm. Using a set of coils for the shunt to **G**, with shunt r having a multiplying power n_1, a convenient deflection d_1 would be taken on **G** through **R** ; the equivalent deflection (such as would be given if the galvanometer were unshunted and its scale long enough) being $d_1 \times n_1$. Then x would be substituted for **R**, and another convenient deflection d_2 read on **G** with another shunting value of r having a multiplying power n_2, giving an equivalent deflection $d_2 \times n_2$.

Then $x = \frac{d_1 \times n_1}{d_2 \times n_2} \times R$

$$\text{or } \frac{\text{equivalent deflection with R}}{\text{equivalent deflection with } x} = \frac{x}{R}$$

The foregoing methods depend upon the comparison of the currents through the two resistances to be compared.

192. FALL-OF-POTENTIAL METHODS. If a current be passed through two resistances in series, then the respective p.d.'s will be in the direct proportion of the resistances. If we have a resistance of known value, we can measure the value of an unknown resistance by passing the same current through the two resistances, and comparing the fall-of-potential across the unknown with that across the known resistance. This gives a simple method of comparing resistances if we happen to possess suitable voltmeters. But it is much more difficult to obtain instruments to measure pressures than it is to procure those for currents. The resistance of most ammeters can be made very low, which is what is necessary; but the only voltmeter with an extremely high resistance, the requisite for accuracy, is the electrostatic type. Hence the best methods, which are based on the comparison of pressures, either involve the use of electrometers, or depend upon the potentiometer; which is a means of comparing pressures without taking any current from the terminals of the appliances across which such pressures exist.

If the resistances to be compared are low, and if they will safely carry currents enormously in excess of anything taken by such voltmeters as are at hand, then they may be coupled up in series as in Fig. 201. E will divide into two portions—

V_1 the fall of potential across **R**, and V_2 that across **X**. The current being the same through **R** as through **X** need not be known. Then—

Resistance of **R** : resistance of **X** : : $V_1 : V_2$, or $x = \frac{V_2}{V} R$.

It is not necessary to use two voltmeters if a **differential electrometer** or voltmeter is available. An electrometer consists of two coatings or plates and a vane or needle which can be charged electrostatically.

Such an instrument is indicated in Fig. 202, where the needle is pivoted on a fulcrum f and the controlling force

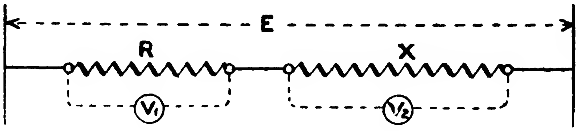


FIG. 201.

is gravity acting on a weight w. The vane is connected to the common junction of R and x and the plates respectively to the other ends of these resistances. If R be varied until the vane is at zero, showing that it is pulled equally to right and to left, then the pressure across R = pressure across x. and as the same current flows through both of these, $x = R$.

One ordinary voltmeter can be used, if it be changed from R to x. In Fig. 203, R is the known resistance, x the unknown resistance, V a sensitive low-reading voltmeter, and B a battery. R, x and B are connected in series: the voltmeter being joined first across the ends of R, as shown by the firm lines; and then across the ends of x, as indicated by the dotted lines. The change of connections could be made by a double-pole change-over switch.

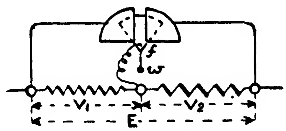


FIG. 202.

The circuit current should be very large compared with that taken by V, so that the conditions are not appreciably altered by placing V across R or across x.

193. THE OHMER. This instrument, which is a practical application of the principle just explained, is used for the measurement of insulation resistance. It consists of an ohmmeter and a hand-generator mounted in one case; but it differs from the ohmmeter in having an indicating portion which works on the electrostatic principle. The scale is graduated to read directly in megohms.

The indicator resembles a multicellular electrostatic voltmeter, described later. It consists of four sets of fixed vanes or "inductors," with 13 in each set; and a moving needle having 12 specially-shaped vanes of mica covered with aluminium.

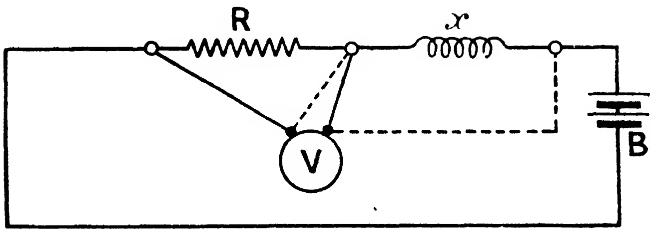


Fig. 203.—Fall-of-Potential Method with One Voltmeter.

The generator is wound to give either 500 or 1,000 volts, as desired, at about 80 revolutions of the handle per minute. The armature is driven through a "free-wheel" gear, which protects the gearing from shock, should the handle be stopped suddenly. The rate of turning the handle does not affect the indications of the instrument; although it must be turned at a fair speed in order to develop a sufficient e.m.f. in the generator.

The generator *G*, in Fig. 204, has one of its terminals attached directly to the sets of fixed vanes or inductors *A A* of the ohmmeter; the same terminal being also connected, through a fixed resistance *R*, to the other set of fixed inductors *B B*, and to the outer terminal *L R* is wound on porcelain insulators, and is fitted in the case of the instrument. *A A* and *B B* are respectively connected together. The other terminal of the generator is joined up to the movable vanes, and also to the other outer terminal *E*. The movable vanes are quite free to turn, or in other words, they are not controlled by any force except that exerted upon them electrically by the inductors.

When the insulation resistance between the terminals *L* and *E* is "infinite," there is no current flowing through the resistance *R*, and consequently no drop of volts therein.

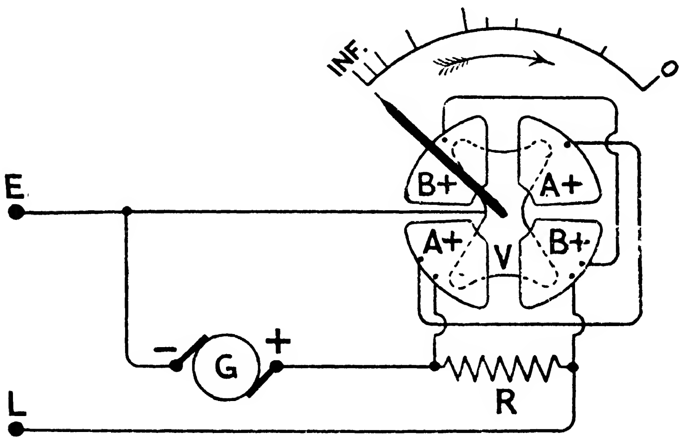


FIG. 204.—PRINCIPLE OF THE OHMER.
(*Nalder.*)

Under these conditions, the potential of *A A* is the same as that of *B B*; and the vanes *V*, owing to their curved ends, take up the midway position shown in the diagram.

When a current flows from *L* to *E*, owing to the resistance under test being less than "infinity," there is a drop of potential between the ends of *R*, due to the current flowing through it. The pairs of inductors *A A* and *B B* are then at different potentials; *A A* being more strongly positive than *B B*: and the movable vanes and needle will turn in the direction shown by the curved arrow. The less the resistance between *L* and *E*, and the greater—consequently

—the current through R, the greater will be the difference between the potentials of A A and B B, and the farther will the movable vanes turn in a clockwise direction.

194. BALANCE OF POTENTIAL METHODS. The methods already described require either two instruments to measure the pressure and current respectively, or two successive measurements of pressures or of currents, unless special apparatus be available. A method of simultaneous comparison of resistances is in practical work more con-

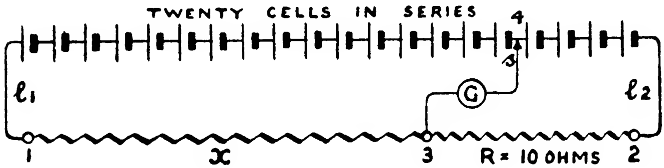


FIG. 205.

venient and if it be a **null method,** or one which merely necessitates the absence of a current or the equality of two pressures to be ascertained, it only calls for a sensitive galvanoscope and does not involve a galvanometer graduated in current or pressure units.

In Fig. 205 twenty similar cells are shown connected in series. These are in circuit with a known resistance R of 10 ohms and an unknown resistance x, whose value has to be ascertained. The leads l_1 and l_2 connecting the battery to R and x are of negligible resistance, so that the full p.d. of the battery exists across the junctions **1** and **2**. This p.d. falls first through x and then through R. There is, therefore, at the junction of x and R, at the intermediate point **3**, a potential which must have a corresponding potential somewhere in the battery. To find this point a galvanometer **G** is connected with one end at **3**, and the other, by a travelling lead and slider s, can be slid along or tapped on the connections between the cells.

Suppose that, when the slider s is making contact at **4**, the galvanometer does not deflect. We are then using it as an "electrical eye" to detect an equality of pressure between points **3** and **4**, and it does for us what an ordinary level would do when laid on a surface and the bubble rests at the mid-position, thus indicating equality of height between the two ends of the level.

If points **3** and **4** are at the same potential, then the rise in pressure due to the e.m.f. of four cells is equal to the drop in pressure due to the resistance of R which equals 10 ohms. Also the rise in pressure due to the e.m.f. of 16

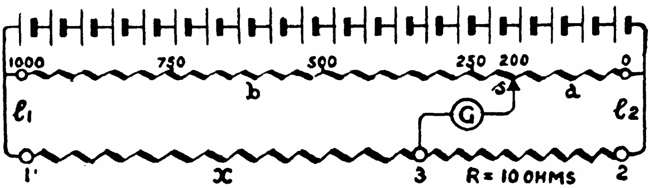


FIG. 206.

cells is equal to the drop in pressure due to the resistance of x or—

Resistance of x : 10 ohms : : 16 : 4

$$\text{i.e. } x = 160/4 = 40 \text{ ohms.}$$

There are three *practical objections* to attempting the test in this way. First, it is difficult to get a large number of cells exactly alike; second, it is expensive in any case; third, the exact point **4** which gives equality with **3** may not be situated at the junction of two cells; in other words, we want to be able to fractionize the p.d. across one cell.

All these difficulties are removed if we make a second circuit of resistance coils, whose values in ohms need not be known but whose relative resistances are known. Thus in Fig. 206 we have coupled a set of coils across the battery. Say there were 1,000 all equal. Then the p.d. across the battery terminals would fall $\frac{1}{1000}$th on each of the coils, so that we could get an adjustment to one in a thousand instead of only one in twenty. The slider s would balance on 200 coils leaving 800 between s and l_1 and the proportions would be—

On coils b and a, 800 and 200.

On series of x and R, x and 10.

Which shows that x = four times R, or 40 ohms as before. This renders it unnecessary to use as many as 20 cells ; the number must be sufficient to give such a fall of pressure down the sets of coils b in series with a as will give an observable deflection in G when s is moved one coil either way.

195. THE BRIDGE METHOD of measuring resistance is widely used in practice, and several more or less kindred

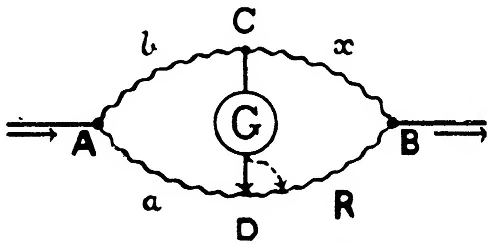


FIG. 207.—THE PRINCIPLE OF THE WHEATSTONE BRIDGE.

methods have been derived from it. It can be proved from first principles by mathematical reasoning, but the preceding section is probably a simpler explanation.

The theory of the set of four resistances, or conjugate conductors, joined up to form a bridge is as follows. If, as in Fig. 207, a current divides at A between the two branches $b\ x$ and $a\ R$, reuniting at B ; it follows that there must be an equal fall of pressure or potential along the paths A $b\ x$ B and A $a\ R$ B, whatever the values of b, x, a and R may be. If a sensitive galvanometer G be connected at a point C in $b\,x$, then—by experiment—a point D may be found in $a\ R$ such that no deflection is given on the galvanometer, and it then follows that the points C and D are at the same potential. This being the case, it is evident as $b\ x$ and $a\ R$ are two parallel circuits, supplied from a common p.d. at **A**—**B**, and as b is in series with x, and a is in series with R that—

$$b : x :: a : R$$

or— $$x : b :: R : a$$

Suppose the points **C** and **D** be fixed, that the resistances a and b be equal, and that x be the unknown resistance. Then, if R be adjusted for balance, i.e. until the galvanometer gives no deflection, $R = x$.

If four 100 volt lamps, selected so that they take the same current, are connected up in bridge form as in Fig. 208 where **CL** represents a carbon lamp and **ML** a metal lamp, and the points A and B be supplied from a 200-volt direct current circuit, a centre-zero voltmeter **V** will show no deflection because C and D will be equi-potential points. If the pressure on $A\ B$ falls, the resistance of the carbon lamps will rise, and that of the metal lamps be reduced, throwing the bridge out of balance and causing a current to flow in one direction through **V**. If the pressure on $A\ B$ rises the resistance of the carbon lamps will fall and that of the metal lamps increase, again throwing the bridge out of balance but in the opposite direction, and the pointer of **V** will move in the reverse direction to the previous case. This arrangement is sometimes used as a volt-indicator to show departures from the correct pressure.

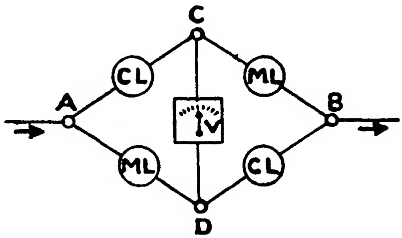


FIG. 208.

Fig. 209 shows a bridge arrangement used by Lord Kelvin in experiments to ascertain the effect of tensile stress upon resistance. *h h* are hooks in the ceiling. To these hooks a battery was connected. A loop of the wire to be tested was fastened to the hooks and hung suspended from them. A weight **W** was fixed to the lower end of the leg x; the remaining portion R hanging freely. To ascertain the alteration in resistance of x due to different weights being placed at **W** a comparator-loop, or slide-wire (shown dotted), was also joined to h h, and a point was found by a slider s where the potential was the same as at the junction of x and R. The proportion of a to b was the same as the ratio of R to x, and any variation in the mechanical stress made it necessary to move s to maintain equi-potential with the junction of x and R.

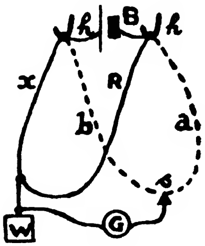


Fig. 209.

196. THE WHEATSTONE BRIDGE arrangement of four resistances is illustrated diagrammatically in Fig. 210. a, b and R are sets of resistance coils, like those shown in Fig. 163, and x is the resistance to be measured. a and b are called the **proportional arms** of the bridge, and are either equal or, for convenience, bear some decimal proportion to each other. **G** is a sensitive galvanometer, Batt. a battery, and GK and BK keys in the galvanometer and battery circuits respectively. x being connected in circuit, some suitable ratio of a to b is selected and R is adjusted until no deflection is obtained on the galvanometer when the keys are depressed.

Then, if a and b be equal, $R = x$.

Otherwise, as $a : b :: R : x$

$$x = \frac{b}{a} R$$

Fig. 210 should be compared with Fig. 207, the arrangement, lettering, and explanations being similar, except that in Fig. 210 **G** is connected with fixed points in the circuit.

197. BALANCE is obtained on the bridge when the needle of the galvanometer does not move on depressing

GK, *BK* having been depressed a second or so before. The dial and pointer of the galvanometer may be represented by Fig. 211. Then a deflection, say, to the right would indicate *R* was too high a resistance, and to the left that *R* was too low. If the battery or the galvanometer leads were reversed, then the deflections would be reversed, but their amount would not be affected. To make sure that the absence of a deflection is not due to the battery being

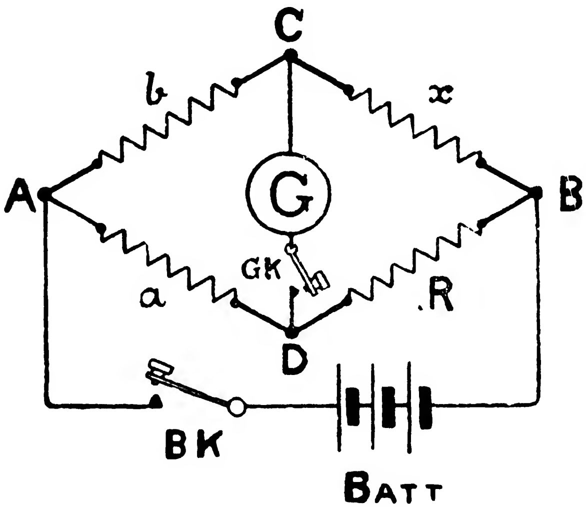


FIG. 210.—WHEATSTONE BRIDGE DIAGRAM.

out of order, or to an open-circuit in the galvanometer leads—either of which would have the same effect as a balance of resistances—it is always necessary to try a unit too much in *R*, and a unit too little. Then if with, say, 299 ohms one got a deflection to the left and with 301 ohms a deflection to the right, while with 300 ohms there was no deflection, it is proved that the last is the balance resistance in *R*.

The student should appreciate the fact that the **adjustment for balance** can be made in several ways. With *a* and b of fixed values, R may be varied by altering resistances in series with one another, or by placing resistances in parallel. If R be invariable, the proportion of a to b may be varied by altering either of these in like manner, or by keeping $a + b$ constant but adding to a what is taken from b. Any method of altering the resistances a, b and R may be adopted to vary the bridge until balance is obtained. Then the three resistance values must be obtained by inspection or calculation and these substituted in the equation, from which x can be found.

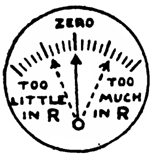


FIG. 211.

198. BRIDGE KEYS. The resistance to be measured generally has some inductance, especially if it be an electromagnet; and it is to prevent the induced momentary e.m.f.'s due to this from disturbing the proper action of the galvanometer that a key is inserted in the galvanometer circuit as well as in the battery circuit. These two keys are shown at *GK* and *BK* in Fig. 210, and may also be seen (unlettered) in Fig. 213. In making a test, the battery circuit should be closed *before* and broken *after* the galvanometer circuit.

Keys have been devised which require only one motion to effect these connections in their proper order. Such a

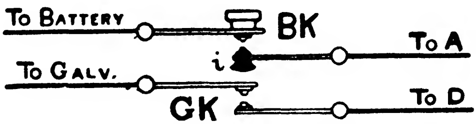


FIG. 212.—SUCCESSIVE-CONTACT BRIDGE KEY.

key is known as a *double* or *successive-contact* key, and is diagrammatically represented in Fig. 212, which clearly shows how it would be joined up in the previous diagram of a Wheatstone bridge circuit. i is an insulating knob which prevents electrical contact between the two keys.

199. PLUG BRIDGES. Fig. 213 represents a form of bridge apparatus. In portable testing sets, the galvanometer is frequently included in the case that carries the coils. For laboratory work the galvanometer is generally more sensitive, a mirror instrument being used in such cases. Any fairly sensitive galvanometer will do for ordinary measurements, as it is only required to prove the equality of potentials at its terminals, i.e. the *absence* of a current through it.

In Fig. 213 it will be noticed that two separate keys are used instead of a double-contact key, and this is the

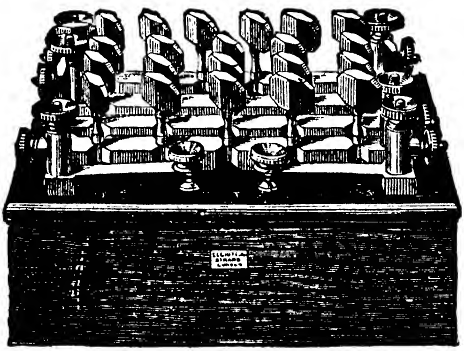


FIG. 213.—POST OFFICE PATTERN WHEATSTONE BRIDGE. (*Elliott.*)

common practice. The right and left-hand keys correspond with *BK* and *GK* respectively.

The six back plugs are in the proportional arms (*a* and *b*) of the bridge, three on one side and three on the other; while of the remainder, sixteen control the resistances in *R*, and two are disconnecting plugs. Some boxes have more coils, and their arrangement and values vary with different makers.

The arrangement of the resistance coils will be seen in Fig. 214. There are two plug-holes marked INF. (infinity), and extra terminals are provided. There are no wires connected across the infinity gaps, and consequently parts of the bridge may be entirely disconnected from one another. This enables the resistances to be used in different circuits.

When inserting plugs, care must be taken to see that they are clean and make good contact, as errors are introduced if the contacts be dirty or loose. When inserting a plug it is a good plan to give it a half turn round in its socket, but very little force should be used.

The common forms of Wheatstone bridge may be used to measure resistances from fractions of an ohm up to

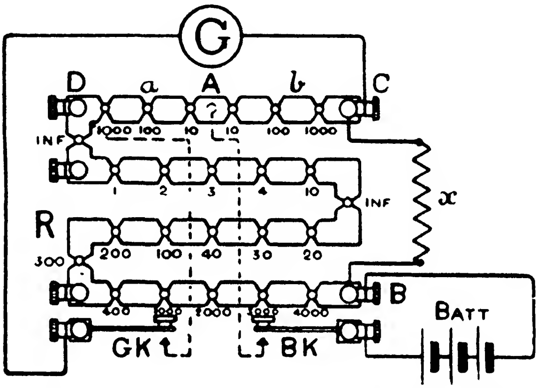


FIG. 214.—ARRANGEMENT OF COILS IN PLUG BRIDGE.

values approaching a megohm: the best range being from say 1 ω to 100,000 ω. The slide-wire and Kelvin bridges are more accurate for resistances under 1 ohm.

Ex. If resistances in arms b, a and R be respectively 1,000 ω, 100 ω, and 5653 ω when balance is obtained, the value of the unknown resistance would be—

$$x = \frac{b}{a} R = \frac{1000}{100} \times 5653 = 56{,}530\ \omega.$$

200. DIAL BRIDGES. Fig. 215 illustrates a pattern of Wheatstone bridge in which, instead of plugs, a number of rotating switches make contact with the various coils, grouped in circles. These switch contacts are inside the box, and so are protected from dirt. The switches are operated by circular knobs on the top of the box, and pointers attached to them indicate what resistances are

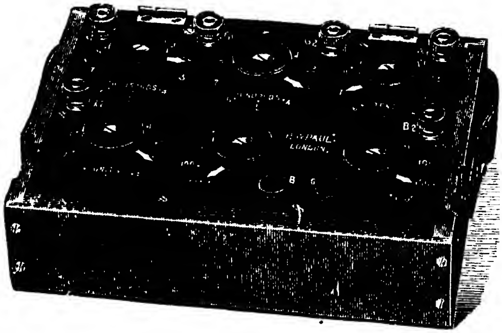


FIG. 215.—ENCLOSED BRIDGE, PAUL PATTERN.

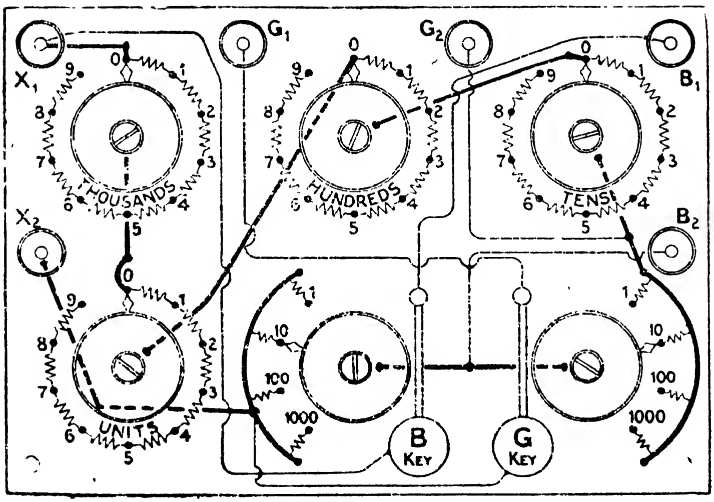


FIG. 216.—CONNECTIONS OF SWITCH-DIAL BRIDGE.

in circuit. Knobs actuate the battery and galvanometer keys, which are also inside. An outer cover is provided, but this is not shown in the illustration.

The terminals on the right (B_1 and B_2) are for the battery, those on the left (X_1 and X_2) for the unknown resistance, and those at the back (G_1 and G_2) for the galvanometer. The internal connections of the apparatus are given in Fig. 216. If these connections be traced out, they will be found to agree with Fig. 214, the divergences having no effect on the essential principles. Thus it will be found that the known resistance is made up of groups of coils which—starting from the point of connection with the unknown resistance—are arranged in "thousands," "hundreds," "tens" and "units"; and that the four

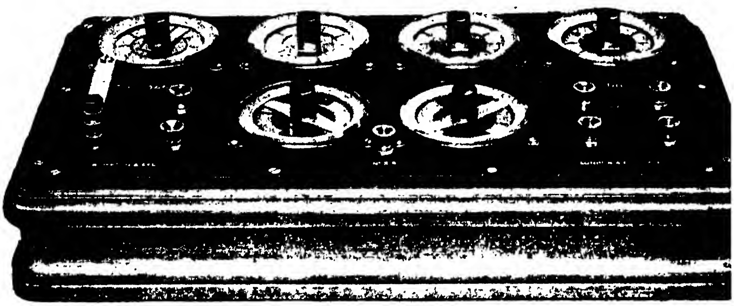


FIG. 217.—STANDARD OR LABORATORY BRIDGE.

ratio coils in each of the proportional arms, 1, 10, 100 and 1,000, are so connected that only one in each arm is in circuit at a time.

For an example of a plug-dial bridge, see the Silvertown set in next chapter. Fig. 217 shows a four-dial decade pattern bridge, with enclosed but visible switches and contacts, and double-contact key, as made by Crompton and Co., Ltd.

201. INTERPOLATION. It occasionally happens that, on attempting to obtain a balance in a bridge test, the change of one ohm in the R arm causes the needle to swing beyond the zero point, and that the simple conditions of balance, given in § 197, cannot be attained. A further decimal place in the result can be found by reading the deflections and using them to find the exact resistance which would give balance. With 1 ohm too little in R the deflection is n divisions to the left, and with one ohm more, i.e. $R + 1$, it is N divisions to the right. Then the divisions on the galvanometer scale equal to 1 ohm are $n + N$ and the actual resistance for balance is $R + \frac{n}{n + N}$

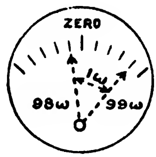


FIG. 218.

Ex. If 98 ω in R gave 1 division left as in Fig. 218, and 99 ω gave 4 divisions right, the 5 divisions would equal 1 ohm, and the pointer would remain at zero if $R = 98 + \frac{1}{5}$, i.e. the balance resistance would be 98·2 ohms.

Thermo and contact e.m.f.'s due to want of uniformity in temperature, or to contact of dissimilar metals, sometimes upset bridge measurements. Then the test can be taken first with battery as in Fig. 210, and again with battery reversed. The mean is nearer to the true value than either single measurement.

202. THE SLIDE-WIRE BRIDGE or metre bridge is an adaptation of the Wheatstone bridge principle, but is only used for comparing small resistances, which should not differ very much in value.

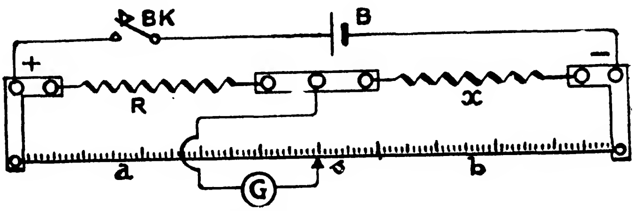


FIG. 219.—DIAGRAM OF THE SLIDE-WIRE BRIDGE.

Fig. 219 shows diagrammatically the construction of the ordinary form of slide-wire bridge. Two copper L-shaped pieces and one straight copper strip have two gaps between them. R is the known resistance inserted in one gap, x the unknown resistance inserted in the other gap, and ab

a stretched wire of any length but of uniform resistance, whose value need not be known. This wire is generally, but not necessarily, one metre long and is made of platinum-iridium or some alloy which is hard and able to withstand wear. The slide-wire *ab* is stretched alongside a scale and is connected at its ends to the two massive copper-strips. The copper strips carry the various terminals and the whole is mounted on a long hard-wood base. One terminal of the galvanometer **G** is permanently connected to the centre terminal and the other with a special form of sliding-key *s*, which may be slid along over the slide-wire and depressed to make contact at any point in its length. The battery **B** and battery key **BK** are connected to the terminals on the L-shaped copper strips.

By sliding *s* along and manipulating the sliding-key, a point may be found on the slide-wire where the potential at that point and between the junction of R and x are equal, as indicated by the non-deflection of the galvanometer. The position of *s* on such " balance " then divides the slide wire into two lengths a and b. These being parts of one uniform wire, the comparative resistances of the lengths, on either side of the point read on the scale where *s* makes contact, will be in proportion to their lengths; and may be expressed by the lengths, say in scale-divisions of a and b as shown by the scale, so that it is only necessary to know these lengths when balance is obtained.

R, which is generally a standard resistance coil, is expressed in ohms; and the value for x will therefore be in ohms. When the galvanometer gives no deflection on depressing **BK** and the sliding-key—then $a : b :: R : x$

$$\text{i.e. } x = \frac{b}{a} \times R$$

For accuracy, the balance point should be as near the middle of the bridge wire as possible. This can be seen by comparing the ratio b/a for, say, the following—

a -	100	200	300	400	500	600	700	800	900
b .	900	800	700	600	500	400	300	200	100
Ratio .	9	4	2·33	1·5	1	·66	·43	·25	·11

The ratio 901/99 = 9·101 and for 899/101 = 8·901, whereas in the centre 501/499 = 1·004 and for 499/501 = 0·996. In the former case each division averages a change of 0·1 and in the latter only 0·004. Therefore, the more closely R can be adjusted to equal x the better the conditions for making a comparison.

One of the practical forms of slide-wire bridge, that devised by Prof. D. Robertson, is illustrated in Fig. 220 on the folder at end of the next chapter.

203. THE DIFFERENCE between the types of bridges is as follows. Referring to Fig. 210 in the coil bridge the galvanometer is connected to two fixed points **C** and **D**, while b, a and R are adjustable resistances. In the slide-wire bridge, the diagonals containing the battery and galvanometer are interchanged and the galvanometer is permanently connected at **B** only, R being generally a fixed resistance, and ab wholly or partly a stretched wire with which the galvanometer makes contact at some point by means of the slider.

As the resistances measured by the slide-wire bridge are generally some fraction of an ohm, it is important that thoroughly good contact should be made between the different portions of the bridge. To this end, instead of ordinary terminals, mercury-cups are sometimes fitted to take the ends of x and R; copper cups, forming parts of the copper straps, are partly filled with mercury and the ends of the different resistances dipped therein.*

The ideas embodied in the slide-wire bridge are to be found in many practical instruments employed in station work, and "fault-finders" are often nothing but such bridges designed for portability and rapid use in the streets.

The battery and galvanometer can be interchanged without affecting the bridge law of balance. For accuracy the galvanometer should be placed between the junctions of the two higher and the two lower resistances in the bridge

* A great deal of information about slide-wire bridges and the methods of using them will be found in Robertson's *Experiments with the Slide-wire Bridge.* (Crompton & Co., Ltd., Chelmsford, 3s.)

lozenge or rectangle. Where a bridge-wire is used, the very practical consideration, that the battery should not be connected so that its current flows to or from the wire, causes the arrangement in Fig. 219 to be preferred, as then there is no risk of the wire being damaged by sparking. In fault-finders the opposite arrangement, that of Fig. 210,

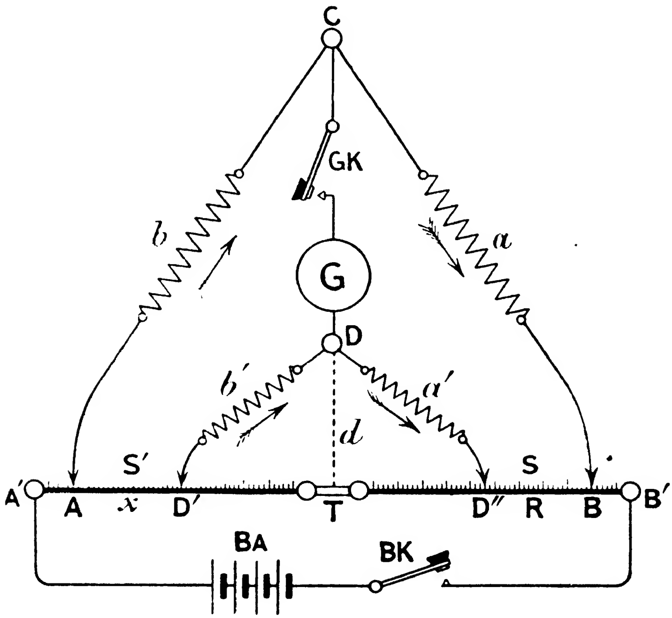


FIG. 221.—DIAGRAM OF ONE FORM OF KELVIN BRIDGE.

has to be adopted; otherwise any e.m.f. in the fault to be located would be liable to upset the accuracy of the test.

204. THE KELVIN BRIDGE gives greater accuracy in the measurement of very small resistances, inasmuch as the errors due to the resistance at contacts are eliminated from the test.

A principle of the Kelvin bridge is given in Fig. 221, where x is a piece of uncovered wire stretched alongside a scale **S′**. **R** is a standard wire with a scale **S** by its side; and a, b and a', b' are proportional arms (or sets of resistance coils). **A**, **D′**, **D″** and **B** are sliding contacts.

If a' and b' were removed, and the galvanometer **G** were connected with the centre terminal **T**, as shown by the dotted line d, the arrangement would resemble the ordinary Wheatstone bridge. There is a disadvantage in the direct connection d, inasmuch as the connection of the wires **R** and x together at the centre terminals would be likely to introduce contact errors. Any resistance due to bad or incomplete contact would prevent the measurement being accurate. Such errors are eliminated by branching the galvanometer circuit through b' and a' to the two sliding contacts **D′** and **D″**. Any similar errors at the slider contacts **A**, **D′**, **D″** and **B** are of no consequence, as they are in series with the comparatively large resistances in the ratio arms. The contact resistances at the other ends of the wires, at **A′** and **B′**, are kept in the battery circuit, where they become negligible and do not enter into the test.

The method of making a measurement is as follows—

The resistance x being inserted, the ratio arms are so adjusted that a bears the same proportion to b as a' does to b'.

Thus if— $a = b, \quad a' \text{ must} = b'$

or if— $a = \dfrac{b}{10}, \quad a' \text{ must} = \dfrac{b'}{10}$

The sliders **D″** and **B** being adjusted to include between them some convenient length on the scale, **A** and **D′** are moved until the galvanometer shows no deflection when the keys are depressed. If this condition cannot be obtained, even by increasing or decreasing the value of **R** between **D″** and **B**; the ratios $\frac{a}{b}$ and $\frac{a'}{b'}$ must be altered, care being taken that they are kept so that $\frac{a}{b} = \frac{a'}{b'}$.

When these matters are adjusted and balance is obtained— $R : x :: a : b$ or $(a' : b')$

$$\text{i.e. } x = \frac{b}{a} R$$

The object of a' and b' is to split the contact and other resistances between **D′** and **D″** so that the proportions shall be in the same ratio as x and R. If, in Fig. 219, these were 1·0 ω and 0·5 ω and the contact resistance between *each* of these to their common junction was 0·03 ω the bridge would balance with b and a giving 1·03 ω and 0·53 ω which is not the ratio of 1 to 0·5. But if, as in Fig. 221, $b' : a' :: b : a$, then the contact resistance of 0·06 ω would be divided in the proportion of x and R, and the balance would give 1·04 and 0·52 which *is* in the proportion of 1 to 0·5.

If x and R were fixed low resistances, with current and potential terminals, they would be connected in series by lead **T**, and the connections would be—

Res. x	left-hand potential terminal to b	: right-hand potential terminal to a	Res. **R**
	right-hand potential terminal to b'	: left-hand potential terminal to a'	
	left-hand current terminal **A′** to **B**$_A$	: right-hand current terminal **B′** to **B**$_A$	

Balance would be obtained by varying the ratio of the proportional arms.

It will be obvious that a Kelvin bridge arrangement could easily be set up in a test room ; but commercial forms are somewhat elaborate in construction. A diagram of one pattern is depicted in Fig. 222 This instrument differs from the arrangement in Fig. 221, in that there is only one sliding contact, viz., **B**, the other points of contact, **A**, **D′**, and **D″** being fixed during a test. **A** and **D′** are in the form of knife-edge clamps in which is fixed the wire, strip, or bar x, the extreme ends of this unknown resistance being connected to the terminals **A′** and **T**. To enable different lengths of conductor to be accommodated, **A**, **A′**, and **T** are adjustable, and are connected with the fixed portions of the apparatus by flexible conductors, as indicated by the wavy lines.

The standard **R** of platinoid is 50 cms. long and has a resistance of about 0·013 ω between the fixed contact point **D″** and the terminal **B′**. Alongside it is fixed a scale graduated in cms., showing the length included between **B** and **D″**. The proportional arms *a*, *a′*, *b*, and *b′* have resistance coils of the values shown, and *RESIS.* is a variable resistance in the battery circuit to enable a secondary cell *BA* to be used without risk of drawing too

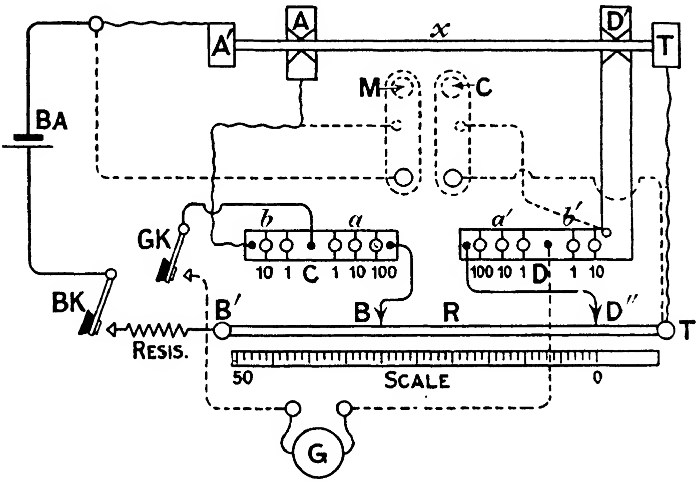


FIG. 222.—CONNECTIONS OF KELVIN BRIDGE APPARATUS.

much current from it. In testing bars, the usual current is from 3 to 4 amps.

R may be read off the scale in centimetres, and the resistance calculated, knowing that the whole length of 50 cms. has a resistance of 0·013 ω. Or the scale might be marked off directly in thousandths of an ohm.

If a conductor has to be dealt with which cannot very well be fixed in the knife-edge clamps **A** and **D′**, its ends are dipped into the mercury cups **M**, **C**. These are carried on movable copper bars which may be connected to the circuit by flexible conductors, as represented by the dotted lines.

205. HOUSMAN'S BRIDGE. To obtain a sufficient p.d. to cause the galvanometer to deflect, the current through a low resistance must be large. High resistances will only carry small currents. By making a comparison in two stages both these conditions can be met.

Suppose x to be about 0·001 ω. It is connected up as in Fig. 223 in series with y, whose value need not be known but may be about 0·01 ω, and R, a sub-standard 1 ω coil, capable of carrying an ampere or two. The bridge is made up with a and b, the usual proportional arms. With both

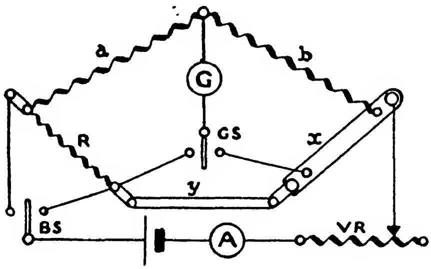


FIG. 223.

BS and *GS* thrown over to the left, the balanced bridge gives $\frac{b}{a} = \frac{x + y}{R}$. The battery, say a large secondary cell, sends an ampere or so through R, y and x in series. The current can be regulated by VR and is indicated by A, but these do not enter into the measurement, although useful precautions to take when making tests with large current cells.

Having got the ratio of $x + y$ to R, the next thing is to find the proportion of x to y. The switches are thrown over to the right, which changes the galvanometer from the junction of R and y to the potential terminal on x nearest to y. The battery sends a current of a hundred amperes or so through y and x, in series. The a arm now includes the 1 ω coil R. Then, on balancing to new values a' and b' of the proportional arms, $\frac{b'}{b' + a'} = \frac{x}{x + y}$

and $\frac{x}{x + y} \times \frac{x + y}{1} = \frac{b'}{a' + b'} \times \frac{b}{a} \times R = x$

It will be seen that no connections in the important parts of the bridge are altered during the test, which is a good example of step-by-step methods, such as lend themselves to measurements where accuracy is an essential.

206. STANDARD CELLS. A standard of e.m.f. is afforded by the *Clark standard cell*, which gives an e.m.f.

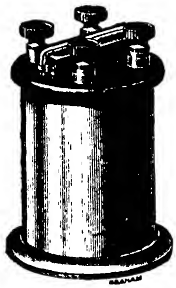


FIG. 224.—CLARK STANDARD CELL.

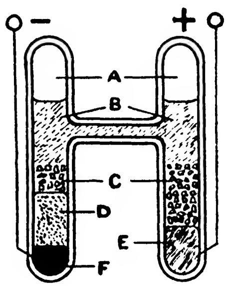


FIG. 225

of 1·433 volts at 15° C. An external view of a couple of cells in a case is given in Fig. 224. Its construction is briefly as follows. The positive element consists of a small quantity of pure mercury contained in a glass test-tube. On the top of the mercury is a paste formed of mercurous sulphate and zinc sulphate, and in this dips a rod of pure zinc which forms the negative pole. Contact is made with the mercury by means of a platinum wire, which is shielded from the paste by a glass tube, or by being fused into the glass containing vessel.

The other standard cell which has been found reliable is the Weston, which, like the Clark, consists of mercury for the positive element, *E*, Fig. 225, but has cadmium sulphate, with mercurous sulphate as a depolarizer, as the electrolyte *B*. Cadmium sulphate crystals *C* are added to keep the electrolyte saturated. Cadmium amalgam, *D* and *F*, forms the negative pole, and *A* are air-spaces above the electrolyte. The e.m.f. is 1·0183 volts at 20° C., and varies less than that of the Clark cell with temperature changes. The glass vessel in most standard cells takes a form like an *H*.

These cells are merely standards of e.m.f. and must only be used on open circuit, or in series with a very high resistance. Their real use is in conjunction with a potentiometer.

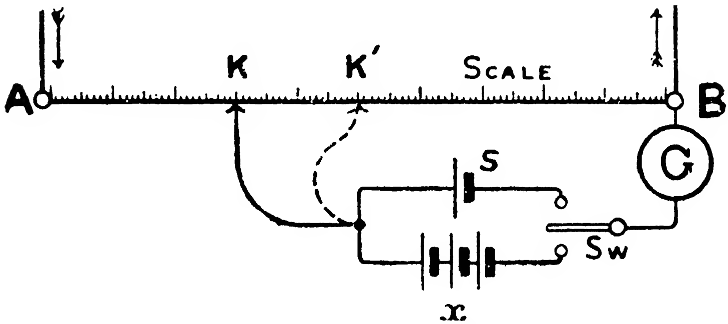


FIG. 226.—POTENTIOMETER METHOD OF MEASURING E.M.F. OR P.D.

207. POTENTIOMETERS. There are a number of methods of measuring e.m.f. or p.d., whose principles depend upon the fact that there is a uniform fall of electrical pressure or potential along a conductor of uniform resistance. Such methods are termed potentiometric methods, and special arrangements of apparatus for such measurements are called *potentiometers*.

In Fig. 226 **A B** is a platinum-iridium or manganin wire of uniform material and cross-section, its resistance, therefore, being proportional to its length. A scale is fixed alongside so that the distance from either end of any determined points in the wire may be at once ascertained. **G** is a galvanometer, **S** a suitable standard cell of known e.m.f., **K** a tapper key which may be slid along **A B**, *Sw* a two-way switch, and x the battery whose e.m.f. is required.

A current is sent along **A B** from some convenient constant source (such as a secondary battery in good condition), and a uniform drop of potential is thus maintained along the length of the wire. *Sw* is first placed so as to connect **G** with x; and **K** is then slid along **A B** until a point **K** is found, such that there is no deflection of **G**. We then know that the tendency of the p.d. between **K** and **B** to send a current round the bye-circuit **K** x **G B**, is exactly balanced by the e.m.f. of x. In the same manner, *Sw* being placed to connect **G** with **S**, a point **K′** is found, by sliding the same key along and making contact with the wire, such that the known e.m.f. of **S** is exactly counterbalanced by the p.d. between **K′** and **B**.

It then follows that—Known e.m.f. **S** : unknown e.m.f. x : : p.d. **K′ B** : p.d. **KB**.

But p.d.'s along **A B** are proportional to lengths.

Therefore—$S : x :: \text{length } K'B : \text{length } KB$

$$\text{and } x = \frac{KB}{K'B} S \text{ (volts)}$$

The practical forms of potentiometer are made direct-reading by inserting an adjustable rheostat in the battery circuit in which the slide-wire is included. This rheostat is adjusted so that when the standard cell is connected the reading for, say, 1·433 volts is 1,433 divisions on the scale. Then each scale-division equals $\frac{1}{1000}$th of a volt. The methods of extending the slide-wire resistance without increasing its length, and of sub-dividing the total resistance are described in § 212.

If an accurate ammeter be employed for finding the value of the current flowing through the slide-wire, and if the slide-wire be carefully adjusted, the standard cell may be dispensed with. Suppose that the resistance of 100 divisions of the slide-wire is 0·1 ohm, and that the current is adjusted to 100 milli-amps., then the p.d. along the slide wire will be 100 × 0·1 = 10 milli-volts, so that each division will represent $\frac{1}{10}$th milli-volt.

The advantage of the potentiometer is that no current is taken from the points between which the unknown p.d. exists. The potentiometer does indirectly what the electrostatic voltmeter does directly, but the former can be given a much longer range than the latter so far as a single instrument is concerned. Moreover, the potentiometer is a most convenient means of measuring p.d.'s of low value, whereas an electrostatic instrument below 30 volts must be of the torsion or reflecting type which is

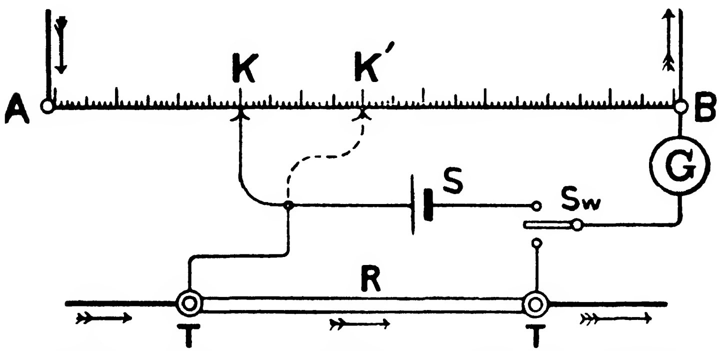


FIG. 227.—POTENTIOMETER METHOD OF MEASURING CURRENT.

unsuited for work outside of a laboratory. The potentiometer makes a very practical instrument in a works' test room

208. POTENTIOMETER MEASURING CURRENT. For the measurement of current the arrangement of apparatus is as shown in Fig. 227, where **A B** is the potentiometer wire. **R** is a platinoid strip of known resistance and of sufficient cross-section to carry the current *C* to be measured without heating.

When the current to be measured flows along **R**, there is a certain p.d. between its ends, and (i) this is balanced against the fall of potential in **A B** by means of the sliding key **K** and the galvanometer **G**; the switch **S***w* being placed on the lower contact. (ii) **S** is then put in the galvanometer circuit by means of **S***w*, and a point **K′** found with the same key, such that the e.m.f. of **S** is balanced by the p.d. between **K′ B**.

It then follows that—

$$\text{p.d. on } \mathbf{R} : \text{e.m.f. } \mathbf{S} :: \text{length } \mathbf{K\,B} : \text{length } \mathbf{K'\,B}$$

$$\text{i.e. p.d. on } \mathbf{R} = \frac{KB}{K'B} \times S \text{ (volts)}$$

$K\,B$ and $K'B$ being expressed in scale-divisions, and S in volts.

The resistance of **R** being known, the current flowing in R $= \dfrac{\text{fall of potential along } \mathbf{R}}{\text{resistance of } \mathbf{R}}$.

The wires from the galvanometer switch and sliding key should be connected to the potential terminals on **R**, so that any possible bad contacts between the main leads and the current-terminals are not included in the potentiometer circuit.

It will be observed that the only difference between the last two tests is that the current-carrying strip **R** in the test for current takes the place of the battery x in the test for e.m.f.

Care must be taken to connect the p.d. to be measured and the fall of potential along the slide-wire so that they oppose one another. Further, the e.m.f. or p.d. to be measured must be less than the total fall of potential along the slide-wire, otherwise no measurement can be obtained.

209. POTENTIOMETER MEASURING RESISTANCE. The resistance **X** to be measured, and a standard resistance **R** of known value, are connected up in series with a secondary battery **B***a*, and an adjustable resistance **AR**. The double-pole two-way switch **S***w* is so joined up that either the p.d. between the ends of **X**, or that between the ends of **R**, can be connected between the end **B** of the slide wire and the tapper key **K**. It is not necessary to know the actual values in volts of the p.d.'s between the ends of the resistances in the above test, and hence no standard cell is necessary.

The potentiometer leads are connected across the standard resistance by throwing **S***w* over to the right, and the p.d. on **R** is balanced on the potentiometer slide **AB**, say at **K′**.

The potentiometer leads are connected across the resistance to be measured by throwing **S***w* over to the left, and

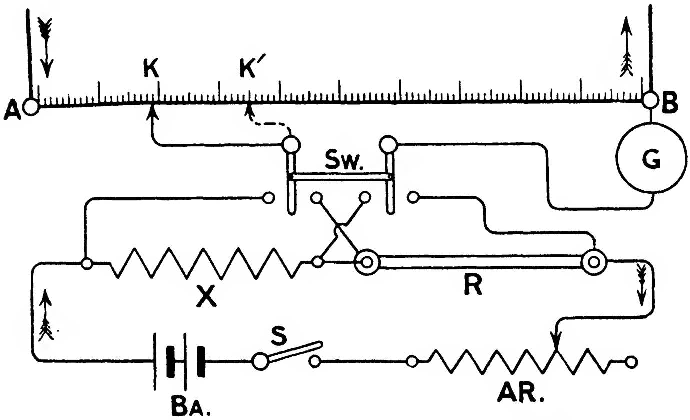


FIG. 228.—POTENTIOMETER METHOD OF MEASURING RESISTANCE.

the p.d. on **X** is balanced on the potentiometer slide, say at **K**.

As the current flowing through the standard and the unknown resistance is the same, and during the test is constant—

$$C = \frac{\text{drop across standard}}{\text{resistance of standard}} = \frac{\text{drop across } \mathbf{X}}{\text{resistance of } \mathbf{X}}$$

and the drops are respectively proportional to the lengths **BK′** and **BK**, **K′** and **K** being the number of scale-divisions from the common end **B**.

$$\text{Then } x = \frac{\mathbf{K}}{\mathbf{K'}} \times R$$

Ex. $R = 0{\cdot}01\ \omega$ and x is a cable: balance is obtained on R with 200 divisions and across x on 8,306 divisions. Then—

$$\frac{200}{0{\cdot}01} = \frac{8{,}306}{x} \text{ or } x = \frac{8{,}306}{200} \times 0{\cdot}01 = 0{\cdot}4153\ \omega.$$

If an accurate ammeter be employed for finding the value of the current flowing through the resistance **X**, and if a standard cell be available for the calibration of the potentiometer in volts, the standard resistance may be dispensed with. The process of *calibration* consists in finding the length of potentiometer wire whose p.d. is equal to the e.m.f. of the standard cell. The circuit connections

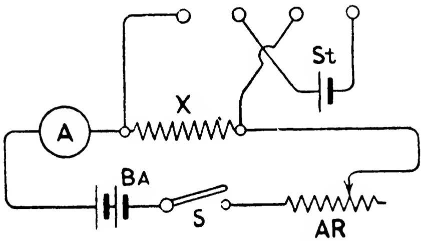


FIG. 229.—POTENTIOMETER METHOD OF MEASURING RESISTANCE.

to the terminals of the two-way switch will then be as given in Fig. 229, where **S***t* is the standard cell and **A** the ammeter. The actual value of the p.d. on **X** is thus obtained, and knowing the current flowing, its resistance x will be—

$$x = \frac{\text{drop across X}}{\text{current through X}} \text{ (ohms)}$$

It will be obvious that this is merely a variation of the ammeter-voltmeter method; the potentiometer taking the place of a voltmeter to measure the p.d. across the unknown resistance.

The resistance of an armature could be taken accurately by passing a large current, measured by **A**, through cables connected to the terminals of the machine, and joining the potentiometer leads to copper knife-edges secured in chisel handles. These "testing-spikes" would be pressed on segments of the commutator, between which the resistance was required.

The lay-out of apparatus for potentiometer tests is illustrated in Fig. 230, on the folding plate at end of next chapter.

210. COMPARISON OF BRIDGE AND POTENTIOMETER. It has been shown that the proportional arms of a Wheatstone bridge and a potentiometer are similar electrically. In each case there are two resistances *a* and *b*, whose values need not be known but the proportion between them must be known. A long stretched wire as indicated in Fig. 231 with a slider *s* making contact on it at any point 2 between the extreme terminals 1 and 3, is the simplest arrangement to meet this requirement. This

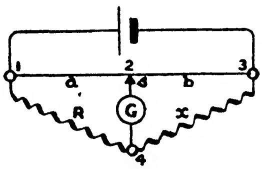


FIG. 231.

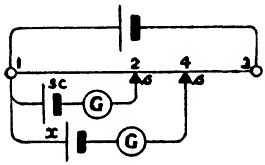


FIG. 232.

is quite a good device when the other resistances in parallel with 1 and 3 are low, as in the comparison of low resistances by the metre bridge. When the resistance between 1 and 3 must be relatively high, either the wire must be very long or very thin, or one box of coils must be used for *a* and another for *b*. An intermediate arrangement is to coil the wire, 1 to 3, on a cylinder, providing some mechanical dodge to make contact at any point along its length.

A comparison between the slide-wire bridge and slide-wire potentiometer is shown in Figs. 231 and 232. In the bridge the p.d.'s across *R* and *x* are compared with the fall of potential along the slide wire and a point 2 on the slide-wire is found, by moving the slider *s*, where the p.d. between 1 and 2 is equal to that from 1 to 4 and there is equality of potential between 2 and 4. In the potentiometer the e.m.f. of *SC* is compared with the fall of potential along the slide wire, and a point 2 on the slide-wire is found where the p.d. from 1 to 2 is equal to the e.m.f. of SC. Then another point 4 is found where the p.d. from 1 to 4 is equal to the e.m.f. of x.

211. POTENTIOMETRIC RHEOSTATS. An ordinary rheostat does not give close adjustment; it usually consists of an insulating tube upon which the resistance wire is wound, and the slider moves parallel to the axis, so that one turn at a time is cut in or out of circuit. Then the slider enables the resistance between 1 and 2 to be varied by jumps of the value r, the resistance between one contact and the next. In Fig. 233 the cylinder is fixed and the slider moves along its supporting rod, parallel to the

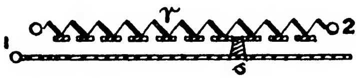


FIG. 233.

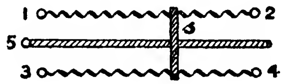


FIG. 234.

cylinder; this rod making contact with the slider and forming the terminal 1.

Sometimes there are two resistances side by side, as in Fig. 234, and the slider bridges the points where contact is made on each of these. This shortens the construction and enables the rheostat to be used (*a*) all in series, current entering at 1 and leaving at 3, or (*b*) in parallel, current entering at 5 and leaving at 1 and 3 joined together. It should be noted that in the latter case the current-carrying capacity is doubled, but the effective total resistance is quartered.

Ex. An electro-magnet with its coils joined up in series is required to be joined up in parallel; how could this be done, and to what extent would the (*a*) total resistance of the coils, and (*b*) their current carrying capacity be altered by so doing?

(*a*) Quarter original R; (*b*) double current.

A rheostat is used potentiometrically when the supply is connected to its two end terminals, and the slider makes contact at some intermediate point.

In Fig. 235 the high voltage battery **HVB** is connected to 1 and 2. Suppose a voltmeter **V** had to be tested throughout its range. It is placed in circuit as shown and the slider *s* is started at 1 and gradually moved to the right. Then *b* acts as resistance in series and *a* as resistance in shunt to **V**, so that as the movement is continued the pressure across **V** is gradually increased.

An application of the potentiometric rheostat is shown in Fig. 236 where *f.m.* is the field-magnet winding of a booster, connected between the slider *s* and midwire earthed-bar of a three-wire system, supplied by dynamo $\mathbf{G}_1$ on the + side and $\mathbf{G}_2$ on the − side. When the slider is in the central position both terminals of *f.m.* are at the same

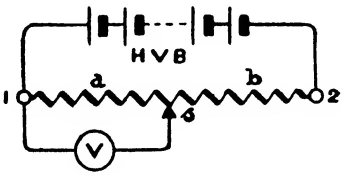


FIG. 235.

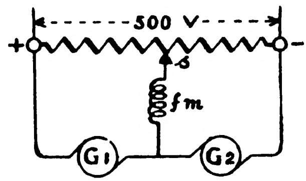


FIG. 236.

potential, but if the slider be moved to the left the upper end of *f.m.* has its potential raised and current flows downwards through it. If the slider be moved to the right, the upper end of *f.m.* has its potential lowered and current flows upwards. If the booster added volts, or gave " + boost " in the former case, it would substract volts, or give " − boost " in the latter case.

212. FINE ADJUSTMENT. There are four ways in which a fine adjustment can be obtained with coils used as the principal resistances in *a* and *b*. These may be either the proportional arms of a bridge, or the equivalent of an extended wire for a potentiometer, or a universal shunt. First: Two boxes each of 10,000 ohms, adjustable to 1 ohm, may be placed in series, and only 5,000 ohms used on each side of their junction to start with. By adding to one side whatever is taken out of the other, the total resistance of a and b is not altered but the proportion of a to b can be made anything desired.

The method of **projection of potentials** may be applied to the comparison of very small resistances if both R and x are provided with potential terminals. In Fig. 237 x is connected in series with R by means of heavy conductors. From the extreme terminals T_1, T_2 of these resistances, where the main current enters and leaves, leads are taken to the outside terminals of a couple of 10,000 ohm resistance boxes. To the intermediate junction of these boxes is connected a sensitive galvanometer, with its other terminal

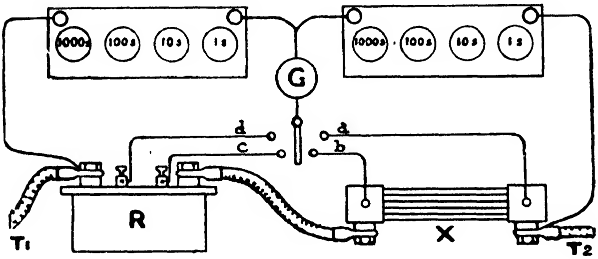


FIG. 237.

joined to a four-way switch. At first all the resistance is in the left-hand box and no resistance in the right-hand box. As large a current is passed through from T_1 to T_2 as R and x can safely carry. Resistance is then transferred from the left-hand to the right-hand box, keeping the total resistance in the two boxes constant, until no deflection is observed on **G**. This operation is repeated for each of the potential points, a, b, c and d. If the resistances in the left-hand box corresponding to each of these balances be A, B, C, and D, then

$$x = \frac{A - B}{C - D} \times R$$

This method should be compared with Fig. 219, and it will be seen that it corresponds to plotting out on a fixed resistance of 10,000 ohms, the equipotential points at each of the four points a, b, c and d. The drop across x corresponds to $A - B$ and the drop across R to $C - D$.

Second: Coils may be used for the principal resistance and a **subsidiary slide wire** inserted **in series** with them, just as linear scales are often marked off in major divisions, and to the left of the zero there is a unit sub-divided into fractions. An example is the Elliott fault-finder

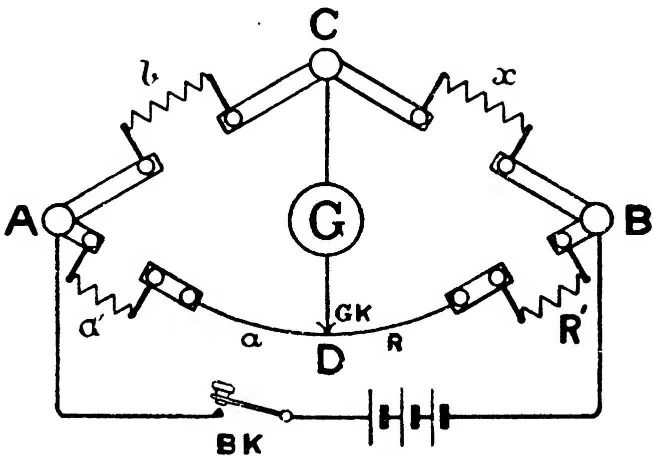


FIG. 238.

in the next chapter. Such an arrangement applied to a Wheatstone bridge is shown in Fig. 238.

Known resistances are inserted at a', b, and R', and the unknown resistance at x. a' and R' should have about the same value if b can be made approximately equal to x. Then, when balance is obtained—

$$a + a' : b :: R + R' : x$$

$$\text{i.e.} \quad x = \frac{(R + R')}{a + a'} b \text{ (ohms)}$$

b is expressed in ohms, and a, a', R, and R' in cms.; the values of a' and R' (in terms of the number of cm. divisions along the wire a R to which their resistances are equal) having been previously found. a' and R' are, in fact, merely prolongations of the arms a and R.

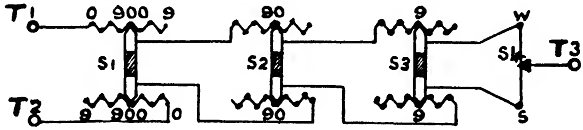


FIG. 239.

This method is embodied in some of the most accurate potentiometers, for which a simplified scheme of connections is given in Fig. 239. Between terminals T_1 and T_2 there is always 1,000 ohms. Along the top row there are nine coils of 100 ohms, nine of 10 ohms and nine of 1 ohm, and the same along the bottom row. S_1, S_2 and S_3 are sliding switches with insulating handles, hatched in the diagram, carrying contact levers at each end. Moving them to the left cuts out resistance on the top row and inserts an *equivalent* amount in the bottom row. Fine adjustment is made by the slider S_4, connected to T_3, which makes contact on *SW* whose resistance is 1 ohm. If *SW* be divided into 1,000 parts, then the p.d. between T_1 and T_2 can be split into any desired fraction at T_3; the device giving an adjustment of $\frac{1}{1000}$th of 1 ω in 1,000 ohms or 1 part in a million.

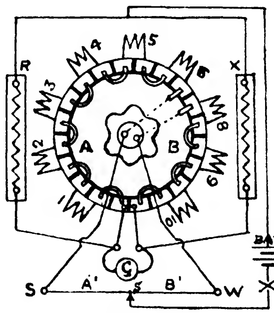


FIG. 240.

Third: An excellent form of variable resistance is shown in diagram in Fig. 240 coupled up as a bridge, where **R** is the known and **X** the unknown resistance, G the galvanometer. **SW** is the slide-wire, and there are nine coils made up of the same resistance as the slide-wire, which in this case is shown inserted between coils Nos. 6 and 8. A disc of ebonite carries U-shaped lever-fingers which connect the fixed contacts, between the coils, in series, except in one instance where two straight fingers bear upon the contacts. These are seen between the right-hand end of coil 6 and left-hand end of coil 8, so that **SW** takes the place of coil 7, giving a minute adjustment, say to $\frac{1}{100}$th part. Thus arm A of the bridge includes coils 1 to 6 inclusive, and the portion of **SW**, A', while arm B includes the other portion of **SW**, B' and coils 8, 9 and 10. The bridge, therefore, is adjustable to 1 in 10,000; since, by turning the handle in the middle, **SW** can be **inserted between any pair** of the coils. The only objection to the device

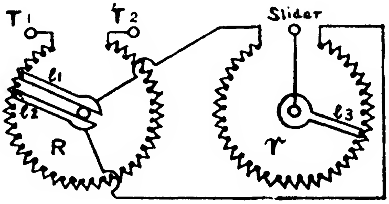


FIG. 241.—KELVIN VARLEY SLIDES.

is the expense entailed in making such a complex switch, which must have a uniform and extremely low contact resistance.

Fourth: The sub-division may be effected by placing another or **minor resistance in parallel** with a portion of the major resistance, in a similar way to the employment of a Vernier on a scale, or in a micrometer, to obtain fractions of the smallest unit of measurement on the principal scale. In Fig. 241 **R** is the principal resistance consisting of 101 coils, each of 1,000 ohms. Across two of these—any two depending upon the position of the two contact levers l_1 and l_2—is joined in parallel the subsidiary resistance r, consisting of 100 coils, each of 20 ohms. The resistance between T_1 and T_2 is therefore $(99 \times 1{,}000) + (2{,}000/2)$, since $20 \times 100 = 2{,}000$ ohms are in parallel with $2 \times 1{,}000$ ohms, or a total of 100,000 ohms. l_3 corresponds to the slider in previous diagrams.

Each of the foregoing arrangements is of the potentiometric type, and may be used either as the proportional arms of a bridge, as a potentiometer, or as a fault-localizer.

QUESTIONS

1. Describe how resistance coils are made, what materials are generally employed, and mention the uses to which such coils are put.

2. Sketch the details of a box of resistance coils. Describe the method of winding, and say what is the object of the particular manner in which resistance coils for testing purposes are wound.

3. What do you mean by the statement that the temperature coefficient of platinoid is less than that of copper, and what bearing has this upon the use of the former alloy for resistance coils ? What generally would guide you in the selection of the gauge of wire to be employed for any particular resistance ?

4. Describe the construction of a coil of 1 ohm resistance intended as a standard of comparison. State what material you would select for the wire. Sketch the form you would employ, the mode of winding and insulating it.

5. In what form would you make a resistance intended to carry large currents and yet have a very accurately determined value, stating the material you would employ ?

6. How would you make a cheap resistance, the magnitude of which could be altered at will, to be used for strong currents ? Give a brief specification.

7. You have to make a resistance of one-hundredth of an ohm to carry 20 amperes without overheating. Describe the procedure and show how, by means of such a resistance and a galvanometer capable of measuring very small currents, any current up to the carrying capacity of the resistance could be measured.

8. A resistance to take 0·015 ampere at 2,000 volts is required for a wattmeter to be used on an a.c. circuit. Give particulars of how you would construct it.

9. Give a sketch showing how you would make a linesman's detector galvanometer. Why is one coil wound with thick and the other with thin wire ? How would you proceed to obtain the value in amperes of the arbitrary graduations of the "quantity" coil ?

10. Sketch and describe some form of high resistance reflecting galvanometer with moving needle, and say why such instruments are so much more sensitive than those with pointers. Explain the use of the controlling magnet.

11. Describe some form of moving coil galvanometer, giving sketches of its parts. Show how the current flows through it, and how the deflections of the coil are read on a scale.

12. What is the difference between a needle and a suspended coil mirror galvanometer, and what special advantages do each possess ? Why is it better to fit the base of any instrument, required to stand steadily, with three levelling screws rather than four ?

13. Distinguish between (*a*) absolute, (*b*) sensitive, (*c*) dead-beat, (*d*) astatic, and (*e*) differential galvanometers; and in the case of (*c*) explain by what means the particular action observable is obtained.

14. Explain the general principle of the tangent galvanometer and say how its arbitrary readings are converted to absolute measure. What are the essential points in a tangent galvanometer in order that the readings may be proportional to the tangent law?

15. If you had a tangent galvanometer, the correctness of whose indications you doubted, how would you proceed to verify the same if you had a battery of negligible resistance and a set of adjustable resistances available for making a test?

16. Two battery cells are joined in series through a tangent galvanometer, the two cells acting in the same direction, a deflection of 60° is produced; the two cells are then joined in opposition, and the deflection obtained is 30°. What are the relative strengths of the two currents and the proportional e.m.f.'s of the two cells? *Ans.* 3 : 1 and 1 : 2.

17. Assuming the deflection of 60° in the foregoing question to be obtained with the galvanometer unshunted, what should be the resistance of a shunt which would reduce the deflection to 30°, the galvanometer having a resistance of 1,000 ω and the current flowing through the circuit being the same in both cases? *Ans.* 500 ω.

18. What is meant by a "shunt," and how is the "multiplying power" of a shunt calculated? Show how Ohm's law could be applied to find the relation between the current through the working coil of a shunted ammeter and that in the main circuit.

19. Why are shunts for sensitive galvanometers usually made one-ninth, one ninety-ninth, and one nine-hundred-and-ninety-ninth of the resistance of the instrument? Of what material should such coils be made?

20. Give a sketch of a shunt box having high insulation. What should be the resistance of three shunts, so that $\frac{1}{10}$th, $\frac{1}{100}$th, and $\frac{1}{1000}$th of the total current would pass through a galvanometer of 8,600 ohms resistance. How would you wind the wire for the shunts, and where would you place it to diminish the temperature error as much as possible? *Ans.* 955, 86·9, and 8·61 ω.

21. A battery is connected through a very high resistance to a galvanometer of 4,500 ohms resistance shunted with 1,500 ohms, the deflection obtained being 200 divisions; what shunt would be required to increase the deflection to 300 divisions, and what would be the deflection if shunt were removed? *Ans.* 2,700 ω : 800 divs.

22. A galvanometer of 5,000 ohms resistance and shunted with 500 ohms gives, with a certain current, a deflection of 300 divisions; what is the multiplying power of the shunt, and what shunt would be required in order that with the same current the deflection may be reduced to 100 divisions? *Ans.* $n = 11 : S = 156\frac{1}{4}\ \omega$.

23. Describe the arrangements for shunting a galvanometer so that when it is shunted down the total resistance of the circuit in which it is shall not be thereby changed, and give an example of the numerical working out of the proper values to give to the coils of a constant-current shunt.

24. Give a diagram of the connections of a "universal shunt" and show why it can be used conveniently with any ordinary galvanometer.

25. What are the means employed to increase the range of instruments for measuring voltage and current ?

26. A certain direct-current ammeter has a resistance of 0·01 ohm and may be used for measuring currents up to 2 amperes. Give the resistance of the shunt that would enable currents to be measured up to 20 amperes. *Ans.* 0·00111.

27. A direct current voltmeter has a resistance of 100 ohms and a scale divided into 150 equal parts. A deflection of 100 divisions of the scale is obtained with a p.d. of 1 volt between the terminals. Explain how this instrument can be used for measuring up to 150 volts, and give a diagram of connections. *Ans.* 9,900 ω in series.

28. Given a voltmeter of 2,000 ohms resistance and two coils of 1,000 and 4,000 ohms resistance, what will the supply voltage be (*a*) when the three are in series across the mains, and (*b*) when the 4,000 ohm coil is in series with and the 1,000 ohm coil in parallel with the voltmeter, the voltmeter reading 100 volts in each case. *Ans.* 350 v. : 700 v.

29. Explain why, if a galvanometer of low resistance has first a large battery cell and then a small battery cell connected to it, the deflection obtained in the first case is larger than it is in the second ; but if the galvanometer has a high resistance the deflections in both cases will be approximately the same.

30. A galvanometer of low resistance has first a single battery cell and then a number of cells connected to it, and it is found that the deflection produced in both cases is approximately the same ; with a galvanometer of high resistance the number of cells gives a greater deflection than the single cell. Why is this the case ?

31. What is the essential difference between an ammeter and a voltmeter ? The resistance of a milli-voltmeter is 1 ohm and has a full-scale deflection of 100 milli-volts. What are the values of the resistances, and how are they connected in circuit, so that the instrument can be used (*a*) as an ammeter, reading 5 amperes, and (*b*) as a voltmeter reading 100 volts ? *Ans.* $\frac{1}{49}$ ω in parallel : 999 ω in series.

32. State exactly how you would determine the strength of a current if you knew the resistance of a wire through which the current was passing, and you had a galvanometer of high resistance and a battery of known electromotive force to test with.

33. How would you measure the resistance of a wire by using an ammeter and a voltmeter without any auxiliary resistances ? Give a sketch of the connections you would make.

34. The current taken by a circuit consisting of a lamp and a voltmeter in parallel is 1 ampere. What is the resistance of the lamp if the reading of the voltmeter is 200 volts, and its resistance is 2,000 ohms ? *Ans.* 222·2 ω.

35. The current taken by an incandescent lamp is 0·16 ampere as read by an ammeter of negligible resistance. On connecting a voltmeter of 100 volts range across the lamp, the ammeter reads 0·26 ampere. Calculate the resistance of (*a*) the lamp, and (*b*) the

voltmeter. Explain why the readings of the two instruments do not give the true resistance of the lamp, and how you would connect the voltmeter in circuit so that they do. *Ans.* 625 ω and 1,000 ω : voltmeter across L and A in series.

36. An incandescent lamp has a resistance of 1,000 ohms, a voltmeter 4,000 ohms, and an ammeter 1 ohm. The voltmeter is to be connected either (a) directly across the lamp, or (b) across the lamp and ammeter in series. Explain which of the two methods gives the least error when the supply voltage is 200 volts. *Ans.* (b) error 0·1% ; (a) gives 20% error.

37. Describe a differential galvanometer and state why the two coils must have equal resistance, and also equal magnetic effect. State how you would measure the value of a resistance by means of such a galvanometer.

38. In how many ways could you measure the resistance of a wire, and which would give the most accurate results in the case of (a) a short length of heavy cable, (b) a coil of wire of about 20 ohms, and (c) the secondary of an induction coil ?

39. Black lead or graphite is said to be a conductor of electricity. How would you proceed if you were required to measure the resistance of a streak of black lead made by drawing a finely-pointed black-lead pencil across the surface of a piece of slate or of ground glass ?

40. It is said that glass, when beginning to soften by heating, becomes a conductor of electricity. By what experiment could you ascertain the truth or falsity of the statement ?

41. Describe some simple experiment to show that while the resistance of an iron wire increases with temperature, that of a carbon filament decreases as the temperature is raised.

42. Some carbon and metal lamps are given you with the request that you will obtain the cold and hot resistances. How would you proceed to determinate accurately these quantities ?

43. On a 200-volt circuit the current passing through a " bank " of lamps is found to be 12 amperes, but, on inserting a length of cable in series with the lamps, the voltage across the lamp terminals is found to be 195. Suppose that it is permissible to earth the circuit for a short period, how could you test the ohmic resistance of a lightning conductor within easy access of this lighting circuit ?

44. Explain the principle of action of the Wheatstone bridge, and prove the relation which must exist between the four arms when balance has been obtained. Show that battery and galvanometer can be interchanged.

45. Choose four different values of resistance which will form a balanced Wheatstone bridge, and calculate the current in each branch when a pressure of 1 volt is applied to the bridge.

46. Sketch and describe any form in which the Wheatstone bridge is practically arranged, and explain the methods you would employ to compare the resistance of a given wire with that of a known standard resistance.

47. What are the conditions to be fulfilled in a key to be used with a Wheatstone bridge, and describe one fulfilling the conditions. If such a key were not available, what would you do in its place ?

48. Sketch a simple form of Wheatstone bridge, with a stretched wire as the measuring part, and say fully how it is used for adjusting a resistance of 1 ohm with respect to a known coil.

49. You are provided with 3 yds. of bare Eureka wire having a resistance of $\frac{1}{2}$ ohm. per yard, a galvanometer, and a battery. How could you measure and cut off from a bobbin of copper wire a piece having a resistance of 1 ohm ?

50. How would you measure the approximate resistance of a shunt coil if the only apparatus available was a bobbin of German silver wire 0·022 in. diameter ($\rho = 30 \times 10^6$ ohm), a compass needle, a Leclanché cell, and a slide rule ?

51. Give a diagram of the Post Office form of Wheatstone bridge, showing the connections, and state the lowest and highest resistance you can measure on it with fair accuracy. What difficulties are met with in measuring low resistances, and how are they overcome ?

52. What is a dial bridge, and how are its coils connected ? Compare its advantages and disadvantages with slide wire and Post Office pattern bridges.

53. In measuring a resistance by means of a plug bridge, it is found that when 1,000 ohms are unplugged in the bridge, the galvanometer needle has a deflection of 13 divisions to the left of zero, but when the resistance unplugged is increased to 1,001 ohms, a deflection of 21 divisions to the right is obtained ; what would be the resistance that should give balance ? *Ans.* 1,000·382 ω.

54. Describe the arrangement of apparatus, and method, specially adapted for measuring accurately the conductivity of the copper in a thick copper bar, and show how it differs from those used for resistances of higher values.

55. State the law of the Kelvin double-bridge, pointing out its advantages, and describe the construction of some form of bridge adapted for comparing standard resistance coils with great accuracy.

56. What is meant by the phrase "copper of 98 per cent conductivity" ? If you had a specimen of insulated wire submitted to you for testing, how could you determine whether the copper forming the conductor is of the specified percentage conductivity, if you had a piece of pure copper wire (of different length and diameter) with which to make a comparison ?

57. Describe the construction of, and the process of preparing and setting up, a Clark standard cell, and the precautions to be taken in using it. How would you compare several such cells together ?

58. Describe the principle of the potentiometer, and make a sketch of the connections, showing how it could be used to measure the e.m.f.'s of different types of cells.

59. Explain how you would proceed to check the accuracy of a voltmeter, reading up to 600 volts, by means of any potentiometer you are acquainted with.

60. How would you calibrate a voltmeter between 100 and 150 volts, having at your disposal 75 secondary cells, a sensitive galvanometer, Wheatstone bridge, Clark cell, thermometer, and 1 megohm resistance ?

61. How would you calibrate an ammeter reading to 100 amperes, if the only standards at your disposal were a Clark cell and low

resistance ? Show in a diagram of connections the apparatus you would require, and describe how you would proceed.

62. Describe the potentiometer method of measuring a current. In such a test, balance is obtained with a scale reading of 1,434 mm. for a standard cell of 1·434 volts e.m.f. What is the error of an ammeter reading 70 amperes when balance is obtained at 695 mm. for the p.d. across the terminals of a 0·01 ohm standard resistance ? *Ans.* ½ ampere high.

63. Give sketches showing the details of construction of a direct-reading potentiometer, and explain how it could be used for the exact measurement of current, and terminal voltage of a large dynamo provided with carbon brushes ; and for the measurement of field resistance and of armature resistance; exclusive of brush contact resistance.

CHAPTER VIII

TESTING AND INSTRUMENTS

213. TESTS for copper or conductor resistance, and of insulation resistance, are constantly being made upon every appliance, and parts of plant, under construction in manufacturers' works. As these things cannot conveniently be taken to, or connected up with, the test-house a number of different types of *portable testing sets* have been devised. In the test-house on a works of any importance there will be found a complete equipment of apparatus for checking and standardizing the less accurate but more portable and convenient combinations which are regularly in use in the shops.

Similarly, the mains superintendent on a supply system must be able to find out the condition of new mains as they are laid, and obtain information from time to time of how they are behaving, and if any changes are taking place in their copper resistance or insulation. Faults on mains have to be *located*, or their position found quickly by electrical tests, so that repairs may be effected at a minimum cost. Further, systematic tests on plant and mains give a record from which experience is often able to judge when a breakdown is likely to occur, so that steps can be taken to put things right before an actual interruption has taken place.

When an electric light or power installation is completed, it has to satisfy certain tests for insulation before an electricity supply authority will connect it to their system. Such an authority is not compelled to give a supply of energy to any premises unless the electric lines and fittings are in good order and condition, and not calculated to affect injuriously the use of energy by other consumers.

The **Institution Regulations*** state that insulation

* *Regulations for the Electrical Equipment of Buildings.* Institution of Electrical Engineers. (Spon, 1s.)

resistance shall be measured with twice the working pressure and that the test shall show not less than 25Ω per point; a "point" being the termination of the wiring for attachment to a fitting for one or more lamps or other consuming devices. The insulation of the case or frame work from the live parts of motors, heaters, and other appliances shall not be less than 0·5Ω. The larger the installation, the lower will be the insulation-resistance.

214. FACTORY TESTS. In the manufacture of a cable, copper wire is stranded up into the size of conductor required, and is then passed through the covering shops where it is insulated. Afterwards it is either lead-sheathed and wrapped with an outside tape soaked in preservative compound, or it is braided and compounded.

A drum, with the cable wound on it, is then sent on to the tank-house where it is dropped into a large tank filled with water, and is immersed for 24 hours at a temperature of 60°F. The water finds its way into any cracks, crevices, or defects, while its temperature and that of the cable become uniform, so that this is known. The completed cable is then tested for insulation, copper resistance, and capacity. From the tank-house, *test-leads* run to the test-house in which the various instruments are located.

The test for **insulation resistance** consists of a special application of the substitution (direct-deflection) method; by comparing the deflection, which a galvanometer gives when a battery is joined up with the insulation in circuit, with the deflection given when a known high resistance R is in circuit with the whole or a known part of the same battery. As the readings on the scale of the galvanometer are proportional to the currents passing through, it follows that the deflections are inversely proportional to the resistances. Thus: Insulation of cable : R : : deflection through R : deflection through cable insulation.

When the galvanometer shunts are used the *equivalent deflection* is taken. This is the observed deflection × the multiplying-power of the shunt employed, and the figure thus obtained is the deflection which would be found if the scale were long enough, and the galvanometer were not shunted.

The typical connections are shown in Fig. 242 where x is, say, a paper-insulated, lead-sheathed cable. **SR** is inserted so that under no circumstances can the battery be short-circuited. **BC** is a battery commutator, enabling the range of tests to be further extended by varying the number of cells; using a few to take "constant" and many to measure the deflection on test lead + cable. It also permits the poles of the battery to be reversed. One

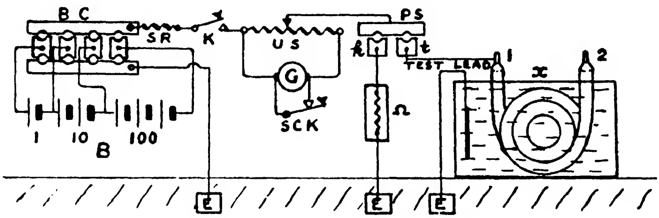


FIG. 242.—CABLE INSULATION TEST IN FACTORY.

plug is inserted in the top left-hand hole and another in the bottom second hole for one cell, or in the third for ten cells, or in the right-hand for 100 cells. With one plug in the bottom left-hand hole and the other in similar positions on the top row of holes, the battery is reversed.

K is the testing-key between battery and galvanometer. **SCK** is a short-circuit key, which is depressed to read the deflections but keeps the galvanometer short-circuited at other times, and allows the charge-current to enter the cable without a throw on the galvanometer needle.

The cable ends are trimmed to a cone so as to reduce surface-leakage to a minimum, and may have a guard ring added, as described later.

215. INSULATION TESTS. The **first step** is to find the "constant" of the galvanometer **G**, which consists in ascertaining the deflection on the scale, produced by the battery **B**, when the circuit includes a standard known resistance, say 1·1Ω made up of a safety resistance **SR** of 0·1Ω and a megohm resistance Ω. The galvanometer is shunted-down by the use of a universal shunt **US**, so that the multiplying power of the shunt is high; suppose it be 1,000. Switching on to the Ω by inserting plug in k, brings $R = 1{\cdot}1\Omega$ into circuit and gives, say, 460 scale-divisions, then the equivalent deflection through 1Ω would be $460 \times 1000 \times 1{\cdot}1 = 506{,}000$ divisions if the galvanometer were unshunted. The value of 1 division on the scale is therefore 506,000 megohms.

The **next step** is to change-over to the test-lead, which will be used to connect the cable to the test-house by plugging in at t. This lead cannot be perfectly insulated and any leakage on it must be known. It is highly insulated, so no shunt is used on the galvanometer. Under these conditions the deflection with the test-lead alone is, say, 20 divisions.

The **third step** is to connect the test-lead to the cable at 1, with end 2 insulated, and to read the deflection due to the leakage current on cable + test-lead, say, 206 divisions. Then the net deflection, that due to the cable alone, is $206 - 20 = 186$ divisions, which gives the insulation as $506000/186 = 2720\Omega$ for the 220 yard length.

To obtain the insulation resistance per mile, which will be less than that of the 220 yard length in the inverse proportion of the lengths: $\frac{220}{1760} \times 2720 = 340\Omega$. This was taken at 62°F. at which temperature the temperature coefficient of paper dielectric is 1·086 so the corrected insulation for the standard temperature of 60°F. is $340 \times 1{\cdot}086 = 370\Omega$ per mile.

Suppose two cables are under test, the first made up of three cores or conductors, each core being 7/·048; and the second a four-core of 7/·028.

The figures for the first core have been worked out in full. In the same way each core of the cable would be tested and the data set down, thus—

Length yds.	Size of cable.	Core tested.	Shunt used.	Total defl.	Defl. leads.	Net defl.	Ω per mile.	Temp. F°.	Ω per mile at 60°F.
220	3 core 7/·048	1	1	206	20	136	340	62	370
		2	1	193	20	173	366	62	398
		3	1	183	20	163	387	62	420
220	4 core 7/·028	1	1	353	20	333	190	62	206
		2	1	372	20	352	180	62	195
		3	1	343	20	323	196	62	213
		4	1	377	20	357	177	62	192

216. ELECTRIFICATION. When a cable is connected to a battery, the curve showing the current flowing into the

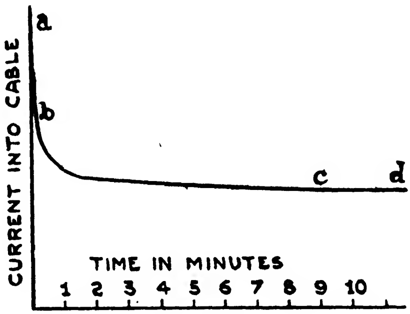


FIG. 243

cable, plotted on a time base, is similar to Fig. 243. It will be noticed that the curve can roughly be divided into three portions. The first part **a – b** is the charging or **capacity current,** which, on closing the circuit, would cause a kick or violent swing of the galvanometer needle were it not provided with a short-circuiting key. This represents the rush of current into the capacity of the cable to charge it up to the same pressure as the battery. The second part **b – c** is the current which represents the quantity absorbed by the dielectric, and this current continues to flow for some time after the circuit is closed ; gradually and steadily diminishing until in the third part **c – d** the curve becomes horizontal, when nothing but the true leakage current through the dielectric remains.

The **electrification** of an insulated cable when measured for insulation is usually expressed by the percentage of the galvanometer deflection d_1 at the end of the first minute, to the deflection d_2 at the end of the second minute after closing the circuit. Thus, if the deflection at 1 min. were 148 divisions and at 2 mins. were 139 divisions, the percentage electrification would be 6·08 per cent.

217. GUARD RINGS. The deflection of the galvanometer in testing insulation of a cable, is a measure of the total current which leaks to earth. This should be only that which passes *through* the dielectric, but it may also include

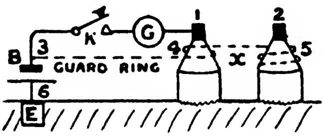


Fig. 244

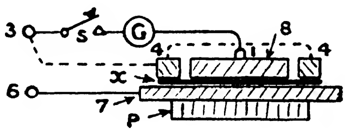


Fig. 245

any which leaks *over* the surface of the trimmed ends of the cable. To get rid of this an extra connection is provided, known as **Price's guard ring,** which acts as a shunt to the galvanometer as far as surface leakage is concerned. Fig. 244 is the same as Fig. 242 simplified, with the guard ring added in dotted line and only the cable ends shown. By connecting the insulated pole of the testing battery at 3 to a bare wire wound spirally round the coned end of the cable x, the surface-leakage current passes from 3 to 4 and 5 and thence to earth, and is not measured on **G**. The leakage through the dielectric passes through **G** on **K** being depressed and flows in at 1 to the conductor, through the dielectric along the length of the cable, thence to earth and back to **B** at 6. As 4 and 5 are at the same potential as 1 and 2 (the drop in **G** being negligible with the minute current through it) the test as already described is not interfered with.

If a piece of insulating material x, in Fig. 245, were being tested it might be supported on one or more pieces of sheet lead 7, on a block of paraffin wax **P**. On the top of x a circular piece of lead 8, with a terminal 1, would be laid. To eliminate surface-leakage from 8 to 7 over the edge of x, a circular guard ring 4 would be laid on x, and connected by the dotted lead to 3, which, with 6, correspond to the battery terminals in Fig. 244.

218. RESISTANCE TESTS. The common methods of comparing resistances may be summarized as follows—

For very low resistances	Housman bridge. Kelvin bridge.
For low resistances	Slide-wire bridge. Potentiometer.
For medium resistances	Plug and dial bridges. Bridge megger.
For high resistances	Direct deflection methods. Megger and similar instruments.
For very high resistances	Loss-of-charge methods.

A factory copper-resistance test by bridge would be worked out thus—

Proportional arms $a = 10$, and $b = 10{,}000$.

(i) Test leads joined together; reading, 360 in R.

$$\text{Then leads} = \frac{10}{10000} \times 360 = 0{\cdot}360 \text{ ohm.}$$

(ii) Test leads connected to ends of cable, reading 3893 in R.

$$\text{Then res. of cable and leads} = \frac{10}{10000} \times 3893 = 3{\cdot}893 \text{ ohms.}$$

Res. of cable $= 3{\cdot}893 - 0{\cdot}360 = 3{\cdot}533$ ohms.

Length of cable 220 yds. and temperature co-efficient at 62°F. = 0·9956; therefore res. per mile at 60°F. $= \frac{1760 \times 0{\cdot}9956 \times 3{\cdot}533}{220}$

$= 28{\cdot}14$ ohms.

For ordinary factory work it is found convenient to use the potentiometer below one or two ohms; the plug or dial bridge for values up to a few hundred-thousand ohms, and the direct-deflection method for anything higher. When insulation reaches such a value that the current is so minute, with the highest battery power available or desirable, that the galvanometer does not give an appreciable deflection, then the same principle is adopted as is applied to, say, a bicycle-tyre thought to be slightly defective ; it is pumped-up hard and left for hours or days, and the lapse of time tells whether it is leaky or not.

The **loss of charge method** is based on the gradual leakage which takes place from a capacity ; the leakage being too small perhaps to be noticed in a short period of time but obvious after a long time. A cable of capacity *K* in microfarads would be charged, taking the place of **K** in Fig. 45, to a pressure *E* and then insulated (by *k* being put in an intermediate position between *c* and *d*) for a time *t* (seconds). At the end of this time its pressure would have fallen to *e*. E and *e* might be measured by a well-insulated electrostatic voltmeter across the ends of *K*. Or, as in Fig. 46, the cable would be charged, giving a throw or swing on **G** of d_1 divisions, and the key would be placed in the position *i* for *t* seconds. Then the key would be raised to *c* to make good what had leaked out, and this would be shown by another and smaller throw, d_2 divisions.

Then insulation in megohms =

$$\frac{t}{2{\cdot}303 \log. \frac{E}{e} \times K} = \frac{t}{2{\cdot}303 \log. \frac{d_1}{d_1 - d_2} \times K}$$

219. OTHER TESTS taken on cables are for **capacity,** by the method described in §66, the throw or swing from a cable on discharge being compared with the throw from a known standard condenser. Then the capacities are in direct proportion to the throws on the galvanometer needle. Capacity measured in this way is not quite the same as the effective capacity with an alternating current, hence it is the practice to take the measurements on supply cables with the kind of current on which they will be afterwards used. There are several methods available for the purpose, but they are rather beyond the scope of this volume.*

Before leaving the factory cables are subjected to a **stressing test** of twice working pressure for half-an-hour. Samples are cut off and tested on **breakdown-tests** to ascertain their dielectric strength; while others are bent round a small drum a certain number of times, **bending-tests,** to find out how mechanical strains affect them.

Samples of the copper wire are tested against standard lengths of pure copper to obtain their **percentage conductivity.** As the figure originally found for "pure copper" was really for copper not quite pure, and as we are now able to procure copper having a lower resistance for a given mass and stated length than the investigators who fixed the standard, we have the anomaly that the best samples to-day have more than 100 percentage conductivity.† The usual percentage specified as a minimum is 98 for commercial work.

Average figures for some sizes of cables in common use, insulated with bitumen and with paper respectively, per mile and at 60°F., are given below—

L.T. Single bitumen cables.

Sect.	Insn.	Res.	Cap.
0·025	268	1·717	0·366
0·050	283	·849	0·575
0·100	250	·416	0·621
0·250	204	·172	0·732
0·500	224	·083	0·732

Paper lead-sheathed cables.

Type.	Sect.	Insn.	Res.	Cap.
(*a*) 3-core L.T.	0·007	499	5·978	0·206
(*b*) Conc. L.T.	0·1	180 and 317	0·413	0·760 and 0·804
(*c*) 3-core E.H.T.	0·1	409	0·415	0·338
(*d*) 4-core L.T.	0·2	190	0·273	0·589
(*e*) 4-core L.T.	0·3	234	0·138	0·645

Of the paper cables, *a* is a pilot cable, *b* a single-phase distributor, *c* a cable for 6,600 volts 3-phase supply, *d* and *e* are 3-phase distributors. In testing, one core at a time is taken to the instruments and the others are joined

* See B. Hague's *Alternating Current Bridge Methods.* (Pitman, 12s. 6d.)

† See R. Appleyard's *The Conductometer and Electrical Conductivity.* (*Elec. Review*, 3s.)

together and earthed. In the case of *b* the first figure refers to the insulation and capacity of the inner core and the second to the respective quantity for the outer conductor.

The variation in insulation-resistance (megohms per mile) for different sizes of conductors in three-core paper

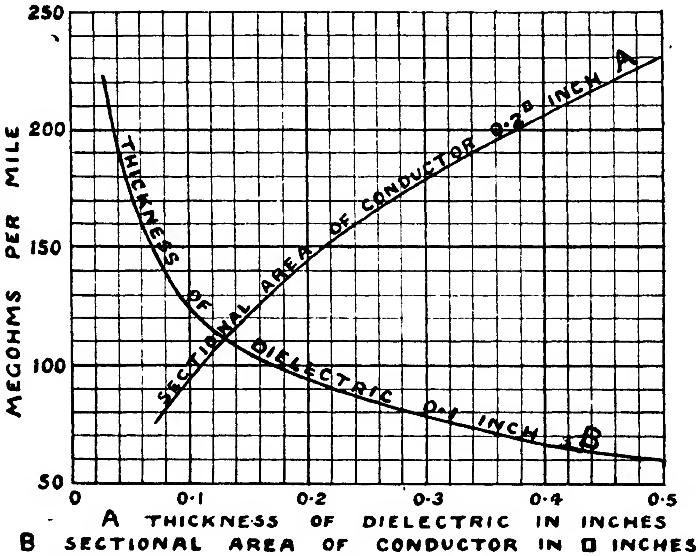


FIG. 246.—CURVES SHOWING INSULATION FOR PAPER CABLES.
(*Callender Cable Co., Ltd.*)

insulated cables is shown by the curve *B* in Fig. 246, where it will be seen that with a constant thickness of dielectric of 0·1 inch, the insulation falls as the copper conductor gets larger. Curve *A* indicates how the insulation rises for a given cross-sectional area of copper in each core, 0·2 sq. in., as the thickness of the dielectric increases. The figures 0·1, 0·2, etc., represent thicknesses of dielectric for curve *A* and cross-sections in square inches for curve *B*.

There are a number of methods of stressing cables, or applying an extra high pressure on the insulation, which employ direct current. The difficulty has always been to find means of raising the e.m.f. to the necessary high value. One which has been developed in practice depends upon the charging of condensers in parallel and then throwing them into series connection for discharge. Another is the use of thermionic valves which act as rectifiers, and enable an extra high pressure, already obtained from transformers, to be made unidirectional.

The advantage of direct current e.m.f.'s in such cases is the absence of the large charging current which always accompanies the application of an alternating e.m.f. of high value to a capacity of many microfarads. When testing a few miles of underground cable at, say, 13,200 volts, even a 100 k.v.a. transformer is insufficient to maintain the charging current without overheating. By the employment of direct e.m.f.'s the charging current has only to be provided once, and it can be controlled by resistances, such as glass tubes filled with water, and allowed to increase slowly. The leading cable-makers now use methods of this nature when they carry out the tests-on-completion of main trunk and transmission lines before handing them over to the purchasers.

The tests now taken by makers of extra high tension cables are insulation, capacity, stressing or pressure tests (with a breakdown test on a sample), dielectric loss (and the power-factor of a charging current on a.c. pressure), with a test on a sample of ability to withstand bending. No single test can be regarded as sufficient to indicate the superiority of one cable over another. These tests should be taken periodically after a cable has been laid so as to ascertain any abnormal deterioration.

220. THE SILVERTOWN TESTING SET is one of the simplest forms of portable testing apparatus. The instrument consists of a box containing resistance coils, galvanometer, shunts and keys. The tests for which this apparatus is used are (*a*) conductor resistance, and (*b*) insulation resistance.

A battery of three *low-resistance* cells, called the "bridge battery," is suitable for the first measurement. For the second a battery of 36 or more small cells, subdivided into sections, called the "insulation battery," is employed. Either of the batteries may be connected with the testing set by means of flexible conductors and plugs.

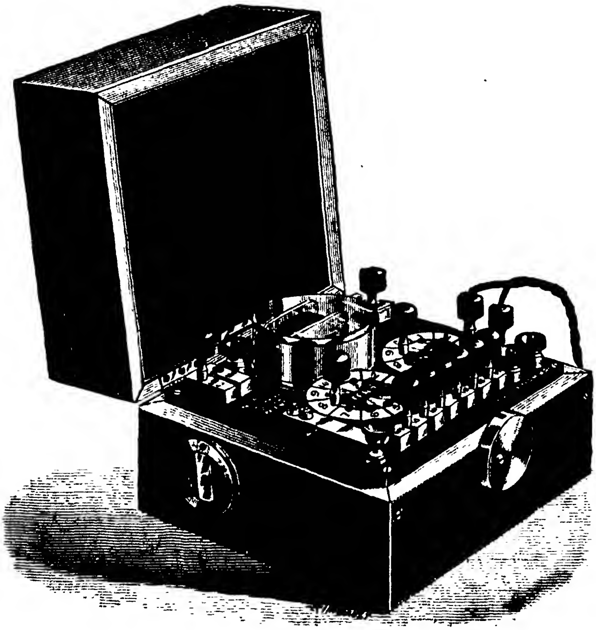


FIG. 247.—SILVERTOWN PORTABLE TESTING SET.

Fig. 248 is a diagram showing the whole of the con nections. The *dial arrangement* of variable resistances for the **R** arm of the bridge should be noted. In the form shown in Fig. 247, there are two "dials," each coil of the first having a value of 1ω, and each coil of the second 10ω. One plug only is necessary for each dial, and to put any required resistance in circuit the plug is *inserted* in the socket opposite the number of ohms required. The plugs are not shown in the diagram, but will be seen in Fig. 247.

The galvanometer consists of a single coil, in which is pivoted a magnetic needle with an aluminium pointer fixed

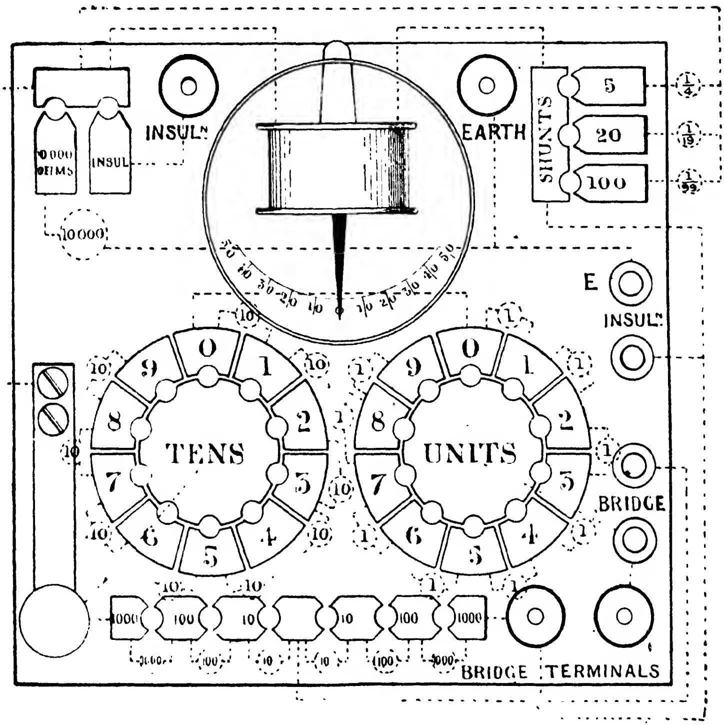


FIG. 248.—SILVERTOWN TESTING SET.

(General connections.)

at right angles. In making a test it is necessary to place the box so that the front faces west; the galvanometer needle—which points north and south when at rest—will then lie at right angles to the axis of the coil. A *controlling magnet*, fitted on the left-hand side of the box, serves to increase or diminish the sensitiveness of the galvanometer. Thus when the magnet's N pole is uppermost, the galvanometer will be most sensitive; while if the S pole be at the top, the deflection of the needle due to any given current will be diminished to nearly one-half. This magnet also serves for adjusting the galvanometer needle to zero.

For a **conductor-resistance test** the "bridge battery" **BB** is connected to the plug holes marked *bridge*; and as there is no battery key, one of these plugs must be withdrawn when it is required to break the battery circuit. The resistance to be measured x is connected with the terminals marked *bridge terminals*. The straight row of

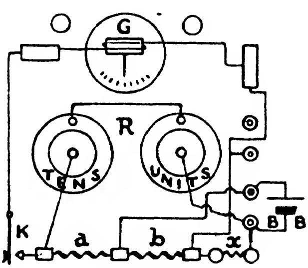


Fig. 249.

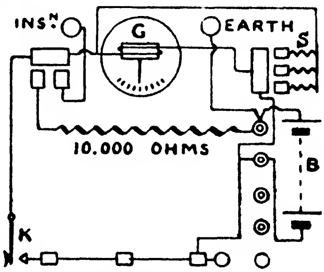


Fig. 250.

resistances forms the proportional arms of the bridge, a and b; the two dials are the known variable resistances, and the key **K** is in the galvanometer circuit.

Fig. 249 is a repetition of Fig. 248 except that those portions of the apparatus not used for resistance by bridge are left out. One plug would be somewhere in the "tens" dial and one in the "units" dial, while two out of three coils on each of the proportional arms would be plugged-up. The proportional arms give a range of from 1000/10 = multiplying **R** by 100, to 10/1000 = dividing **R** by 100.

When a and b are equal, *both* tens, hundreds, or thousands, $x = R$. When they are unequal the following ratios are obtainable—

$x =$	$R \times 10$		$R \times 100$	$R \div 10$		$R \div 100$
In b	100	1000	1000	10	100	10
In a	10	100	10	100	1000	1000

The highest resistance in **R** being 99 ohms, this particular pattern would measure up to $99 \times 100 = 9{,}900$ ohms; the lowest resistance capable of being measured being $1 \div 100 = 0{\cdot}01$ ohm, but this would not be accurate owing to the contact and lead resistances, probably a higher figure than this in themselves.

Other patterns have three dials—units, tens, and hundreds—which extend the range of measurements upwards. A large dial-bridge of this class, but of more elaborate construction, would have four dials; the last being thousands, as well as four resistances in each of the proportional arms.

A dial-bridge has three advantages over the ordinary P.O. pattern; (*a*) the coils are all alike in each set, so that they can be readily adjusted and checked; (*b*) the operation is quicker, only one plug having to be moved to change the resistance, and (*c*) the action of inserting a plug does not affect any others, while the force due to the wedge-like action of the taper-plug acts radially in the dial pattern. Special petticoated-plugs are sometimes used to restrain the blocks in position, and Gambrell Bros. make a form with petticoat outside and taper-plugs inside, which has the advantage of a definite and constant contact resistance.

Fig. 250 shows the connections for **insulation-resistance test,** and is a repetition of Fig. 248, except that those portions of the apparatus not used for insulation test are left out. It will be noticed that the dial resistances and proportional arms are not used. The "insulation battery" **B** is connected with the plug holes marked *Insuln*, and the terminal to the left of the galvanometer is connected with the conductor whose insulation is to be measured, the other end of (and all branches from) that conductor being insulated. The terminal marked *Earth* is joined to earth. The galvanometer may be shunted by any one of three shunts **S**, and according to the position of the plug, $\frac{1}{5}$th, $\frac{1}{20}$th, or $\frac{1}{100}$th part only of the main current will pass through the galvanometer.

It should be noticed that the key **K** now forms a " short-circuiting key " to the galvanometer, and is not in either of the two main circuits which start from the left-hand plug block. By means of the key the oscillations of the needle may be checked. The proportional arm resistances are all plugged up and thereby short-circuited.

When the plug is placed in the left-hand hole in the plug block, the current flows through galvanometer,

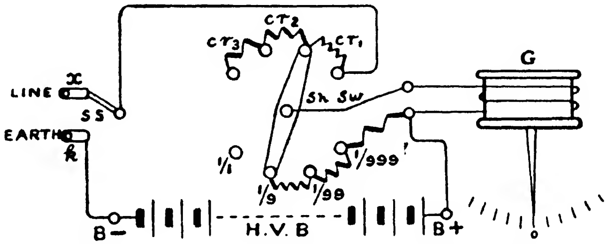


Fig. 251.—Kelvin Portable Testing Set.

resistance coil of 10,000ω and back to battery. When plugged in the right-hand hole, the current flows through **G,** into cable, across insulation, and via sheathing or earth back to battery. The test is taken in the manner already described, the only difference being that the deflection for " constant " is obtained with 10,000 ohms, instead of a megohm or more.

221. THE KELVIN TESTING SET is another portable combination for measuring the insulation resistance of wiring and mains, and may be used with safety with a d.c. pressure up to 250 volts from a supply system. It consists of a delicate galvanometer **G**, of 25,000 ohms resistance, the readings of which may be taken as proportional to the current, and a set of constant-total-current shunts for the galvanometer of values shunting 9/10th 99/100th, and 999/1000th of the main current, from the galvanometer. By means of separate contacts and make-up or compensating resistances cr_1, cr_2, cr_3, in conjunction with the shunt-switch *Sh. Sw.* the resistance of the galvanometer, whether shunted or not, is maintained constant at 25,000 ohms.

In Fig. 251 the shunt-lever is shown on the shunt with a multiplying-power of 10. If it be on 1/1 the compensating resistances are cut-out and the galvanometer is unshunted. **HVB** is a high-voltage battery, and **SS** is a selector-switch which is thrown over to *k* to take the constant, and placed on *x* to take "test."

Ex. In using this set with a battery, the internal resistance of which may be considered as negligible, and shunt $\frac{1}{10}$, the deflection

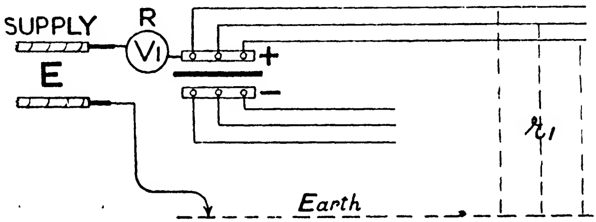


FIG. 252.

obtained with the selector switch, **SS**, on *k* was 15 divisions. On connecting between a circuit and earth, a deflection of 2½ divisions was obtained with the galvanometer unshunted. What was the insulation of the circuit?

The constant of the set was 15 × 100 = 1500 divisions with 25,000 ohms.

The resistance of the circuit $x + G$ was $\frac{1500}{2{\cdot}5} \times 25000$

$= 15000000$ ohms

Deduct resistance of G $= 25000$,,

Insulation of circuit tested $= 14975000$,,

or $14{\cdot}975\Omega$

222. INSULATION BY VOLTMETER. In the case of an isolated installation it is often necessary to make a rough test of insulation resistance, and in the absence of a proper testing set, it is very useful to be able to do this by means of a voltmeter.

In Fig. 252 there are two supply mains between which a steady voltage E is maintained. This is measured by connecting the voltmeter of resistance R between their ends when the instrument will indicate V volts, which represents the value of the very small current that E is able to force through R ohms. The voltmeter is then connected in series between the circuit pressure E and the + side of the installation ; the – pole of the supply being earthed. The deflection on the instrument will be less

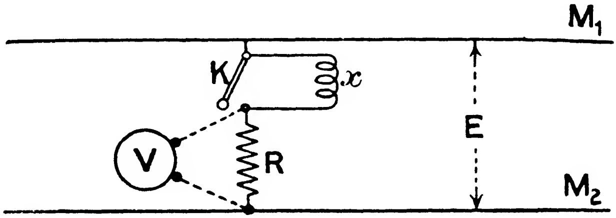


FIG. 253.—RESISTANCE BY THE FALL-OF-POTENTIAL METHOD.

than before, say V_1, and it will be a measure of the current E is able to send through $R + r'$ in series. Then $V_1 : V :: R : R + r'$, and $R + r' = \dfrac{E \times R}{V_1}$, or $r' = \dfrac{E \times R}{V_1} - R$.

By a modification of the above method, a comparatively small resistance may be measured by means of an ordinary voltmeter graduated for such pressures as are used on direct-current supply mains. This modification is useful when the value of the unknown resistance is small compared with that of the known resistance ; and when—in consequence—the two voltmeter readings, if obtained according to the first method, would be very unequal, and the results far from accurate.

In Fig. 253, M_1 and M_2 are the two supply mains (or other source of comparatively high e.m.f.), between which a steady voltage E is maintained : and R and x are the known and unknown resistances respectively, these being connected in series across the mains. K is a key or switch by means of which the resistance x may be short-circuited.

Two readings of the voltmeter are taken ; first with **K** closed, and then with **K** open. Let these two readings be V_1 and V_2 respectively.

Then : $V_1 = E$

and : $V_2 = E - V$, where V is the voltage-drop across x.

$V_2 = V_1 - V$, and $V = V_1 - V_2$

Then : $x : R :: V_1 - V_2 : V_2$

Thus : $x = \dfrac{V_1 - V_2}{V_2} \times R$

223. INTERNAL RESISTANCE. The resistance between the terminals, inside a generator of e.m.f., cannot be

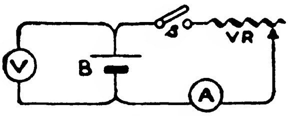


FIG. 254.

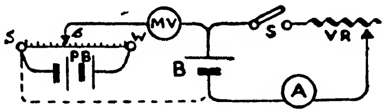


FIG. 255.

measured in the same way as a conductor in which an e.m.f. is absent. It can, however, be obtained by several indirect methods of which the following is probably the most useful in practice in the case of primary and secondary cells.

First, a reading of the open-circuit e.m.f. E is taken by a voltmeter **V** across the cell terminals, as in Fig. 254, such voltmeter taking an inappreciable current to work it. Second, a current C is taken from the cell through a variable resistance in circuit with an ammeter **A**, and the potential drop across the terminals of the cell is measured by **V** under these conditions. Then the internal drop = E - p.d. and this is = $C \times$ the int. res.

i.e. int. res. in ohms $= \dfrac{E - \text{p.d}}{C}$

In the case of a secondary cell it is better to reverse the order of readings and to take the potential drop after the current C has been flowing for some time then to open **S** and note the reading E of **V** *immediately* **S** is opened. The current C must be large, as the internal resistance is low, and the difference between E and the potential drop will be small in any case.

Instead of obtaining the internal drop by the difference between E and potential drop it can be measured directly

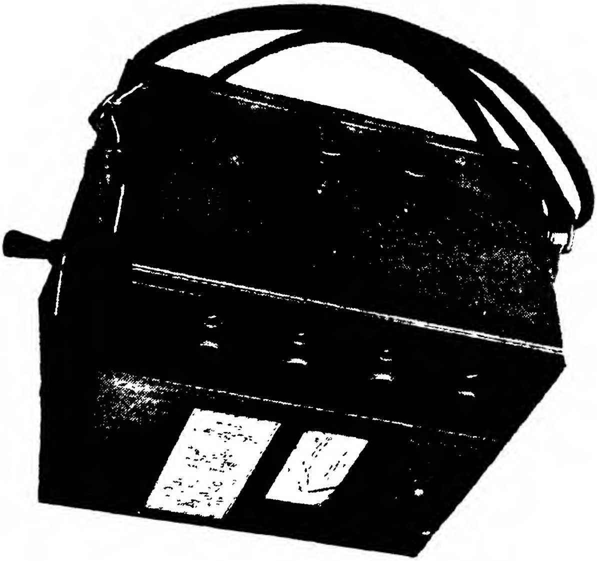


FIG. 256.—EXTERNAL VIEW OF RECORD OHMMETER.

by a milli-voltmeter **MV** as in Fig. 255. If, with **S** open the e.m.f. be balanced against the fall of potential along a potentiometer slide-wire **SW**, which has a battery **PB** connected to its ends, by adjusting the slider until **MV** shows no deflection, then on closing the switch and allowing a current C to flow, **MV** reads the difference of E – potential drop directly on its scale, and internal resistance = milli-volts drop/C. The order could be reversed and the potential drop balanced against **SW**, then on opening **S** the immediate reading on **MV** would give the drop.

224. RECORD OHMMETER. An instrument to measure resistances directly, and which is to be used on different pressures, must have two coils, one acting as a voltmeter and the other as an ammeter. These are rigidly secured to a common spindle and are inserted in the same magnetic field. Consequently, the pointer takes up a position which is the resultant of the two forces. A good example, illustrating this principle, is shown in Fig. 257. The two movable coils are fixed at or near right angles. One serves to give a controlling force, proportional to the pressure, and the other carries the line-current, giving a deflecting force. The pressure coil **PC** and current coil **CC** are placed one above the other. Straight bar magnets of cobalt steel **M** provide the permanent field which passes through the pole irons **I** inside the coils. The resistance in circuit with the pressure coil is marked **R**. The terminals **T** make contact with the circuit from the hand generator.

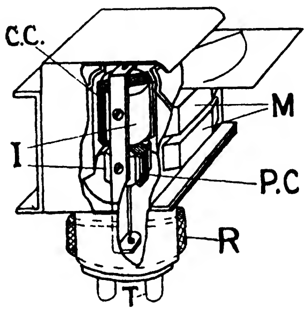


Fig. 257.—General Arrangement of Parts, Record Ohmmeter.

The external view in Fig. 256 shows the containing case of teak, with dial and glass protected by a hinged metal cover, and a carrying or shoulder-strap. By the ingenious slide-arrangement the strap can be pushed sideways, out of the way, when taking readings. The handle of the generator consists of a lever in the form of a round rod, which fits into a sleeve and can be turned flat against the case when not in use. With 150 r.p.m. of the handle the generator gives 500 volts. On a short-circuit the current through the moving coil is 6 milli-amperes.

225. THE MEGGER. Fig. 258 shows the arrangement of the instrument which does away with the necessity for bothering with battery cells. It consists primarily of two permanent bar magnets *NS* and *SN*, which furnish the field both for the generator **G** and the ohmmeter **O** ; the latter acting on the moving-coil principle. The unknown resistance x, which is generally the resistance from the conductors of a system of wiring (*Line*) through the insulating covering to earth, in other words, the insulation resistance, is connected between the terminals on the left-hand side.

The ohmmeter portion has two coils, a pressure coil **P** and a current coil **C**, which carries whatever current leaks through the insulation being measured ; these

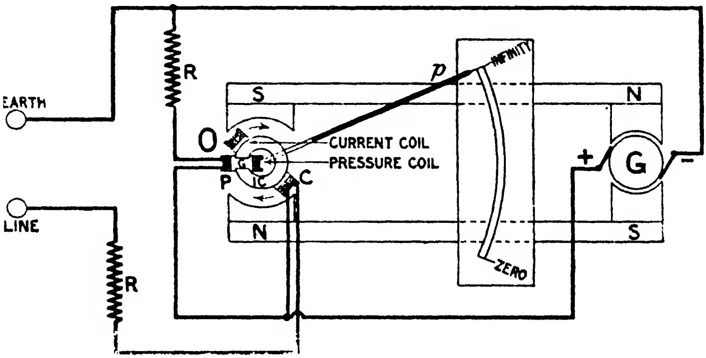


FIG. 258.—PRINCIPLE OF THE EVERSHED MEGGER PORTABLE TESTING SET.

being fixed together at a certain angle on a common axle, which also carries the pointer p of the instrument. The coils move about a fixed soft-iron core **IC** with an air-gap at G ; the current coil **C** embracing this core as a whole, while the pressure coil is threaded by it. The field in which the current coil moves is uniform, whereas that in which the pressure coil moves is weakest in the position shown, and becomes stronger when the coil is deflected. When there is no current in the current coil, that is to say, when the resistance in series with it is infinite, the pressure coil will remain in the position indicated in the figure, the lines of force across the air-gap G tending to keep it in that position. When any current flows through the current coil, the movable part tends to rotate in the direction shown by the curved arrows, the pressure coil being connected in such a way as to resist this motion, and so act as a controlling force. The two coils are connected with the fixed circuits by means of flexible strips, which do not impede their motion appreciably. As the moving system is a compensated coil the apparatus is insensible to the influence of external fields.

RR are resistances for the purpose of preventing too great a current flowing through the coils, for instance, if the *Earth* and *Line* terminals were short-circuited. These instruments are made in a number of standard sizes,

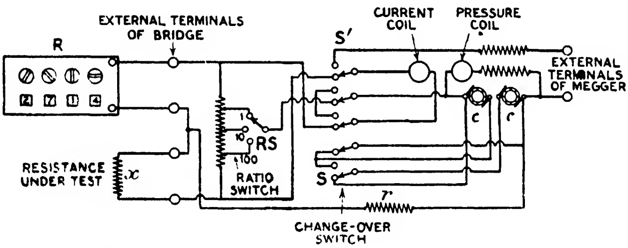


FIG. 259.—DIAGRAM OF THE BRIDGE-MEGGER AND ITS CONNECTIONS.

with resistance-measuring capacities ranging from 10 to 10,000Ω; and with generators giving pressures from 100 to 2,000 volts, the tests being usually made at double the ordinary working pressure of the circuit.

A cheaper and lighter set, called the Meg, is made up in a cast aluminium case with a 500 volt at 100 r.p.m. generator; the indicator reading up to 100Ω. There are two types of generator; one of variable pressure for ordinary work, and the other of constant pressure, where tests have to be made on circuits of large static capacity.

226. BRIDGE-MEGGER. This apparatus consists of a specially-arranged Megger and a resistance box, enabling copper-resistance as well as insulation to be measured. For the former purpose, the Megger is connected to the resistance box **R** (Fig. 259) by two flexible leads, and also to the resistance to be measured x, the generator furnishing the necessary current. The generator armature has two commutators, these being connected to a double-pole two-way switch in such a way that they may be put in series for Megger and in parallel for bridge tests, the pressure in the latter case being halved. The Megger

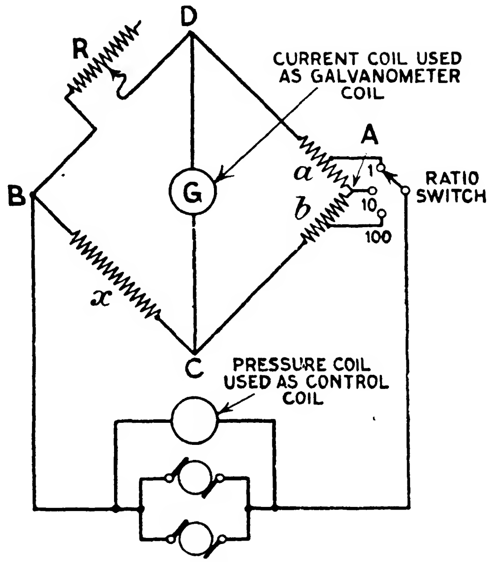


Fig. 260.—Bridge-Megger Connections Simplified.

indicator acts as a zero or " bridge " galvanometer **G** ; and balance is obtained by adjusting the four switch-dials of resistance coils, reading units, tens, hundreds, and thousands respectively, after selecting a suitable proportion of b/a by the ratio-switch. A switch S' (3-pole, 2-way) connects the current coil of the indicator—for the bridge test—to the two outer of four terminals at one end of the box, the Megger terminals at the other end not being used for the bridge test. The middle pole of the switch S'

connects one of the ends of the pressure coil and one pole of the generator to the 3-way ratio switch **R S**, and—according to the position of this switch—when balance is obtained, the unknown resistance x is either equal to, or else 10 times or 100 times that in the switch-dial resistance box **R**, numbers showing through little windows indicating the exact resistance in circuit. In Fig. 259, this value is $2,714\omega$. The two resistance coils just above c, c are those marked **R R** in Fig. 258. One of these is out of circuit in the bridge test, and the other acts as a high resistance in series with the pressure coil, keeping down

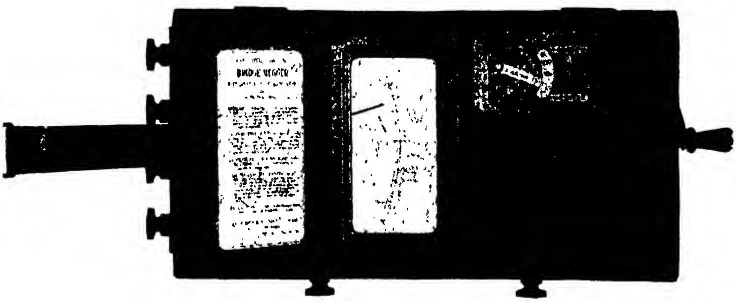


FIG. 261.—PLAN VIEW OF THE BRIDGE-MEGGER.

the current therein. A third high-resistance coil r, which only comes in the bridge test, reduces the current in the bridge. Otherwise this current might be too great owing to the high voltage of the generator compared with an ordinary testing battery.

The current coil acts as the galvanometer coil, the object being so to adjust the resistances that no deflection is given when the handle of the generator is turned. As in the Megger test, the pressure coil acts as the controlling force.

In Fig. 261 is shown a view of the top of the Bridge-Megger box. At the left-hand end are the two pairs of terminals for the connection of **R** and x for the bridge test, while at the bottom are those for the ordinary Megger test. The two switches (S and S' in Fig. 256) are operated by turning the little knob to *Bridge* or *Megger* as the case may require ; and by the side of this is the ratio switch.

If the switches S and S' in Fig. 259 were put in their other positions, for the "Megger" test, it would be found that the connections correspond with Fig. 258.

227. THE DUCTER is a direct-reading instrument for measurements from a few ohms down to one microhm. It consists of two coils set at a definite angle, mounted on a common axle, and swinging in the field of a permanent magnet. In the main circuit, supplied from a battery, is inserted the low resistance x, and a shunt the potential terminals of which are joined to the current or control coil. This coil, therefore, carries a current proportional to the main current. The pressure coil is tapped off potential points on x, and therefore carries a current proportional to the potential drop across x. The movement of the instrument is not controlled by any other forces, so it takes up a position dependent only on the ratio of the potential drop across, to the current through x.

To vary the range of the instrument there are switches which alter the resistances in the circuit of the pressure-coil, of the current-coil, and insert different shunts. To connect x with the instrument, handles with two spikes on each are provided ; the main current being taken through the current-coil and then—

Left-hand handle.			Right-hand handle.	
Spike taking current into x	Spike with potential point	Pressure coil	Spike with potential point	Spike taking current out of x

Three sizes are made, the lowest going down to 1 microhm and the highest up to 5 ohms.

228. THE DIONIC WATER-TESTER is a form of Megger with a special tube for holding the liquid whose resistance is required. The length and bore of the tube and the calibration of the instrument are such that the pointer gives indications on a scale whose unit is the reciprocal of 1 megohm per cm. cube. In one form, the liquid is contained in a U-tube, at the top of each leg of which is a platinum electrode in the form of a ring. The length of the liquid column is 10 cm. and its cross-section 1 sq. cm. With this pattern the scale of the indicator gives 10 divisions deflection with 1Ω, and the scale reads units of conductivity. On a later form the tube is vertical with special arrangements for correcting the length of column of liquid to give indications at a standard temperature of 20°C. The figures given in §29 were taken by an instrument of this class. Meggers, Ducters and the Dionic Tester are made by Evershed and Vignoles, Ltd.

229. TESTS ON COMPLETION. The **first test** after a cable has been laid, or an installation wired, is a rough insulation test with a detector. This shows that there is

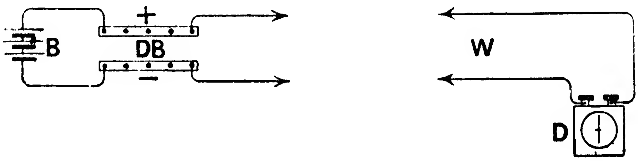


FIG. 262.—CONTINUITY TESTING.

no actual earth connection. The test is repeated between the + and − leads to ascertain that there is no short-circuit.

The **second test** is a continuity test with a detector, Fig. 262. In the case of house-wiring the battery would be joined up to the bars in the distribution board **DB**, all fuses removed except those on circuit of wires **W**, and then the detector **D** should show a current. To prove that this is the current from the battery, at a certain time the battery should be disconnected for, say, 5 seconds and re-connected. The observer looking at the detector should see the deflection go off and come on again.

The deflection of the detector needle would not prove that the connections were perfect throughout their whole length, because a deflection might be obtained through a faulty connection of comparatively high resistance. To check this the degrees of deflection should be noted, a relatively small deflection of the needle compared with what it showed across the battery would indicate this. A more accurate check would be to calibrate the detector by knowing the deflections through different numbers of ohms and roughly estimate the resistance supposed to be in circuit, when the deflection should correspond.

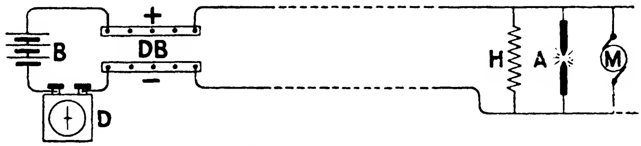


FIG. 263.—CIRCUIT TESTING.

When a circuit has been completed and fittings are in position, it is tested by connecting a battery to the distribution board and going round to each fitting with a detector connected to an adaptor. Alternatively, as in Fig. 263, the detector can be connected between the battery and **DB**, and with the lamps, etc., in circuit, an

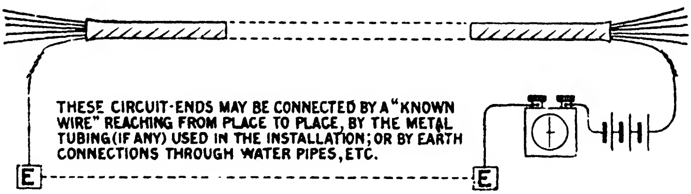


FIG. 264.—SORTING-OUT TEST.

assistant manipulates the corresponding switch for each, say the heater *H*, the arc-lamp *A* and the motor *M*, when the needle of **D** should move in accordance, representing the lighting-up and extinction of each lamp.

The **third test,** where there are a number of wires bunched together or a multiple conductor cable, is a sorting-out of the ends, so that the respective conductors may be labelled at each end, Fig. 264.

When the conductors had been all sorted out and it was known that they were in good condition the insulation copper-resistance and capacity tests would be made. For house-wiring it is generally sufficient to take a test for insulation of each wire to earth, with all others earthed. For this purpose one of the portable testing sets, already described, would be used.

230. EARTHS. This term is employed in two senses. An earth connection may be made intentionally, in which case the intent is to keep bodies so connected at the potential of the earth. An earth may be accidental, or unintentional, in which case it is an earth-fault.

A conductor is **live** when it is electrically charged, and **dead** if it be at zero potential and disconnected from any live system. An electrical system is a combination of conductors and apparatus which are electrically connected to a common source of electromotive force.

A metallic body is **earthed**, or efficiently connected with earth, if it be connected with the general mass of earth in such a manner as will ensure at all times an immediate and safe discharge of electrical energy. The effect of earthing a conducting body is to electrically anchor it, so that whatever may happen its potential does not alter. This is just what is necessary to secure safety, and to ensure that the engineer may know the potentials of everything on or about his system he requires to be able to maintain various parts at definite potentials, so that the system will operate in accordance with design. It is equally important that those other parts which he assumes are at zero potential shall not depart therefrom. One can never be sure that a metallic body disconnected from a live system will remain "dead" as owing to leakage to it it may become charged. The only certain way to maintain it in a "dead" condition is to "earth" it.

231. LOOPED RESISTANCE TESTS. The resistance of an "earth" cannot be found by a single test, because all the methods already described require both ends of the unknown resistance to be accessible. If, however, there are three earth connections available it is a simple matter to find the resistance of each earth by taking them in pairs.

In Fig. 265 there are the earth-plates E_1, E_2 and E_3, with points on their above-ground leads, a, b and c, to which connections can be made. By one of the methods previously explained the resistance between a and b is measured. This includes the resistance from E_1 to the body of earth, and from that to E_2. Let us call this from a to $b = r_1$. Then in a similar manner the resistance is measured between b and c, including E_2 and E_3, $= r_2$.

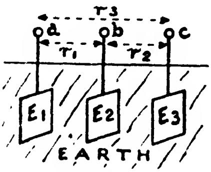


FIG. 265.

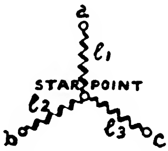


FIG. 266.

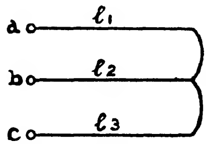


FIG. 267.

Finally a to c is measured $= r_3$. Then we have got each of the earth-contact resistances twice.

To get E_1—

$$\begin{aligned} r_1 &= E_1 + E_2 \\ + r_3 &= E_1 \qquad\quad + E_3 \\ \hline & 2E_1 + E_2 + E_3 \\ - r_2 &= \qquad\ \ E_2 + E_3 \\ \hline \div 2 & \,|\, 2E_1 \\ \hline &= E_1 \end{aligned}$$

Similarly to get E_2 or E_3, add the two measured resistances in which the required quantity occurs, subtract the measured resistance in which it does not occur, and then divide by 2 to get the required quantity.

The example of Fig. 265 shows the importance of providing two or more earth-plates so that the actual resistance of an earth connection can be checked periodically. To indicate what value of resistance constitutes an "efficient earth," the following Board of Trade Regulation may be noted: "an e.m.f. not exceeding 4 volts shall suffice to produce a current of at least 2 amperes from one earth connection to the other through the earth."

In exactly the same way the resistance of each leg of the three-phase winding, Fig. 266 or the resistance of each of three pilot-wires l_1, l_2 and l_3 in Fig. 267 could be obtained. In the former case the junction of l_1, l_2 and l_3 (star-point) is inaccessible, and in the latter the test can be taken from the ends a, b and c by looping together the far ends of the leads.

232. LEAKAGE INDICATORS are instruments for indicating the current leaking to earth, or any decrease in the insulation-resistance of a system. If two lamps are connected in series across a pair of mains they will just glow, if each be suited for the circuit-pressure. If their intermediate junction be earthed, they will still glow equally if the insulation resistance of each main, + and – in Fig. 268 is the same. Should a fault occur on one of these mains, the lamp connected to that main will glow more dimly while the other will brighten. If the fault were a bad one, the lamp connected to the faulty main would go right out, and the other become fully incandescent.

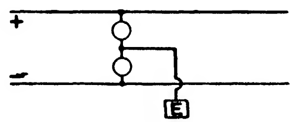


FIG. 268.

If a voltmeter were connected to earth on one terminal and to a two-way switch on the other, as in Fig 269, the pressure to earth could be taken between either side of the system and earth. Two voltmeters may be joined up, instead of lamps, in series across the mains with their middle junction connected to earth. Instead of two voltmeters a differential electrometer, Fig. 202, might be used. Leakage detectors on three-phase systems are often of this type. In mines, for example, efficient means must be provided for indicating any defect in the insulation of a system.

These methods give the relative insulations of the two mains, the higher pressure being measured across the better insulation, but do not give the actual insulation. They are useful because it is very unlikely that faults of equal badness would come on both mains at the same time. Hence they serve as indicators to draw attention to abnormal conditions.

Leakage to earth on a supply system must be recorded. On three-wire systems the neutral is usually connected to earth through a recording ammeter and a fuse, with a resistance of large current carrying capacity and of such a size that the maximum current is limited to 100 amps.

To find the leakage on the + and − mains the earth connection is broken, the pressure from each main to earth is measured, and then each pole is connected in turn to earth through an ammeter. From the readings obtained, the insulation resistance of the system of mains can be calculated.

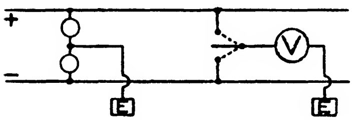


FIG. 269.

These devices and methods tell the station engineer that there is a leakage on his system of mains, and how much, but do not inform him where. Having found that there is something which needs attention, the next step is to get some idea of the locality.

233. FAULTS. The electric circuit consists of a conductor leading from the generator to the consuming device, with insulation round the conductor; and another conductor returning from the consuming device to the generator, similarly insulated.

There are many ways of laying the insulated conductors or cables, forming the mains between generators and consuming devices. Some of these are indicated in Fig. 270 (frontispiece), where the low tension distributing main is composed of three single cables, laid on the solid system, next the building line. Outside this main is a low tension three-wire feeder. Nearer the kerb is a pilot-cable for use with a discriminating protective system, and outside of this is the extra high-tension three-core alternating current feeder or transmission line. See also Chapter XX.

A fault is a failure in either of the conductors, or in the insulation which surrounds either of them. Such a failure generally leads to an interruption of supply to the consuming device, or to an unintentional and detrimental change of pressure.

Where there are two cables laid side by side, the damage or "fault" may be of three kinds: (*a*) a connection to earth on one or the other but not both, this is an *earth*

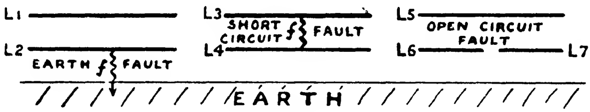


FIG. 271. FIG. 272. FIG. 273.

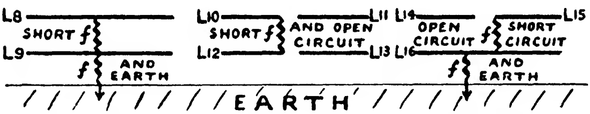


FIG. 274. FIG. 275. FIG. 276.

fault as on L_2 in Fig. 271; (*b*) an undesired connection between the two conductors but not to earth as between L_3 and L_4 in Fig. 272, this is a *short-circuit fault*, or what telegraphists call a "contact fault," and (*c*) a break in one or other of the cables severing the circuit, without either connecting between them or to earth, as in L_6, L_7, Fig. 273, this is an *open circuit fault*. Earths and short-circuits frequently occur together as in L_8 and L_9 in Fig. 274, so do short-circuits and open-circuits, a couple of cables fusing together at their ends and the conductors of one or both parting altogether where they were previously continuous.

L_{10} and L_{12} are short-circuited and their respective continuations L_{11} and L_{13} are open-circuited. L_{14} is open circuited and its continuation L_{15} is short-circuited to L_{16} which is also earthed by the fault *f*.

Faults are " found " or their character ascertained and position located by methods of testing, employing the instruments already described, and based upon the methods of comparing resistances by the fall of potential and Wheatstone bridge, of comparison of capacities, or by the electro-magnetic effects produced by a current in the cable. " Fault-finders " are appliances of the bridge or potentiometer or induction coil type, differing from ordinary patterns in two ways only. First, they are devised to give results as rapidly and simply as possible having regard to the fact that they will be used out-of-doors and often in bad weather, and, second, they provide for the connection of heavy cables, while eliminating the errors due to contact resistances and similar disturbing factors.

The insulation on a cable laid in the street under the paving of a footway or roadway may be damaged by the blow of a pick when the ground is opened to lay a gas-pipe or repair a water-pipe. The insulation may deteriorate at some part where the protection afforded it is imperfect, and electrolysis may result in a failure of the insulation. The insulating sheath of a cable forming one of the " mains" of an electricity supply system may be partially or wholly destroyed in many ways at a particular point ; and there leakage will occur, if the current can find its way back to the generators. If it cannot, then the potential of the system will at least be altered as regards earth ; the leakage point being brought to earth or zero pressure and the rest of the system of mains having pressures measured from this.

234. EARTH FAULTS cause leakage from an electrical system if (*a*) there is an intentional earth somewhere on the same system, or (*b*) if the appearance of one earth fault creates another. In any case it will tend to do so as it is improbable that the normal potential of the various parts of the system is not affected or altered by such a fault coming on it. If the system be well insulated everywhere else—as, say, in the case of a private lighting installation of sound materials and properly erected—

then an accidental connection to earth at any one point will not cause leakage but will merely alter the potentials to earth of the different parts.

235. VOLTAGE-SWINGS. A fault to earth on the mains connected to a dynamo takes the polarity of the main on which it occurs. Thus in Fig. 277 a fault on the top main to the right of S_1 would always be +, and current would leak to earth if there were any return circuit for the leakage current: a fault on the bottom main to the left of S_2 would always be −, and current would flow from earth if there were any return circuit for it. But a fault

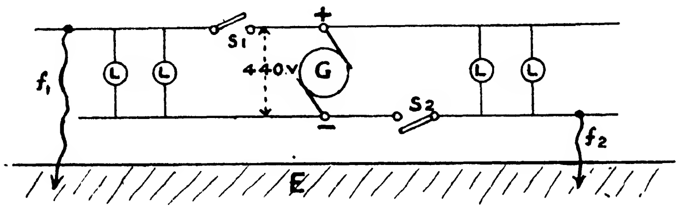


FIG. 277.

f_1 would be − if S_1 were open, and + if S_1 were closed. It would be illusive unless the fault-finder knew this point; if he did, it would guide him to it.

Suppose in addition to the first circuit there happened to be a second, and that S_2 had been placed in the − main in this case. If a fault f_2 came on, either circuit alone—to the left or to the right of G—might be run without anyone knowing of its appearance. But if both main switches were closed there would be a dead short-circuit across G.

With S_1 alone closed the + lead would be at earth potential, and the − lead 440 volts below earth. With S_2 alone closed the − lead would be at earth potential and the + lead 440 volts above earth. Consequently the system would be subjected to voltage-swings, and the insulation would be liable to give trouble. It is this sort of thing which, on 3-wire d.c. systems, has led to fires caused by electrical leakage. For months perhaps the system is normal and then a fault comes on the + or − conductor and the following changes occur—

Main	Normal conditions.	Fault on +.	Fault on −.
+	220 v. above earth.	Earth Potential.	440 v. above earth.
midwire	Earth potential.	220 v. below earth.	220 v. above earth.
−	220 v. below earth.	440 v. below earth.	earth potential.

On a three-wire supply system a consumer is supplied either by a two-wire or by a three-wire service line. If the building be of average size two conductors only are brought in, and these may be connected either between the positive and neutral, or between the neutral and negative, as at **A** and **B** respectively in Fig. 278 for a system with 500 volts between the outers.

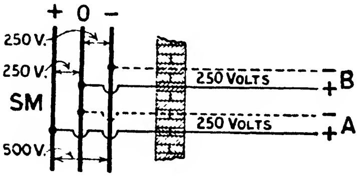


FIG. 278.

An installation is connected to all three mains when the demand for current exceeds a certain limit, or when motors above 2 or 3 h.p. have to be supplied. Three service lines are brought in, as in Fig. 279, and these branch off into

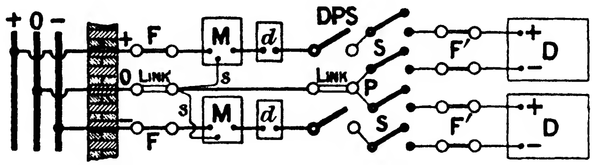


FIG. 279.—CONNECTION OF INSTALLATION TO THREE-WIRE MAINS.

two separate two-wire circuits. It should be noted that the middle wire has no fuse or switch inserted in it, but a link enables it to be disconnected when necessary for testing. This middle-wire is intentionally connected to earth at the generating station, §230.

For further information as to three-wire systems see

Chaps. XIX and XX, Vol. ii; §20 and following in *Electric Wiring Fittings, Switches and Lamps*; and §§61, 62 and 63 *Electric Circuit Theory and Calculations.*

236. FAULT LOCALIZING.* If the leakage of electricity cause a noise, smoke, or shock, the position of the fault is indicated in a similar way to gas or water, as it is made evident to the senses. Sometimes the escaping current jumps across small gaps in the circuit and the effect then produced can be heard. If a leakage of a considerable current takes place from a street main, smoke sometimes rises from the joints in the paving above the fault, or there is a smell of charred insulation. On a rainy day the paving above a fault often dries off quicker than

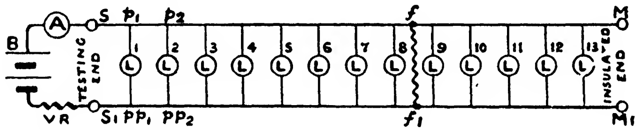


FIG. 280.—LOCALIZING BY FALL OF POTENTIAL.

the remainder of the street, so that the first thing to do is to make a careful inspection.

Electrical tests are relied upon to find the position of, or to *locate a fault.* The methods employed are simple adaptations of the tests already described. They become more complex when the faults are only *partial*, or are imperfect earths of high resistance, or intermittent shorts, or open circuits to low pressures but continuous conductors to high pressures. Or when there happens to be an e.m.f. in the fault itself for some reason or another.

One of the simplest cases is that of a street lighting main, **S M**, with a complete short circuit on it at *f*, Fig. 280. Lamp posts at intervals of about 50 yards have lamps in their lanterns which form parallel bridges across the main. The main is disconnected from the rest of the system, a battery capable of sending a few amperes along the circuit

* General hints on this subject will be found in J. Wright's *Testing and Localizing Faults.* (Constable, 2s.)

S, f, f_1, S_1, is connected through an ammeter to the ends of the main, and the pressure is measured by a milli-voltmeter connected to the contacts in each of the lamp holders in turn, all the lamps being removed beforehand. The pressure measured on the milli-voltmeter at 1 will be the drop in the copper conductors from p_1 to f and back to pp_1. A test is then made at 2, and the pressure must be less as the distance p_2, f, pp_2, is shorter. Continuing along the route of the main 3, 4, and so on, the pressure falls at each lamp-holder until 8 is reached, where it is very low and would be nothing if the fault were in that lamp-holder or close to it. Beyond that point the pressure will be slightly lower than at 8, but will not vary between 9 and 13 because no current is flowing through the mains beyond the fault This is a simple **fall of potential test** which is quite serviceable if the fault is of low resistance, and if branches off both mains at intervals can be readily got at, as in this case.

A leaking current raises the potential of the ground in the neighbourhood of an earth-fault, so one simple method, especially with direct currents, is to probe the earth with contacts connected to a low-reading voltmeter, and trace out the direction of fall of potential.

Ex. (*a*). A leakage of ⅜ths ampere had to be located on a low tension cable on the negative of a 240 volt d.c. system.

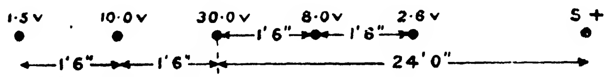


Fig. 281.—Fall of Potential Round Fault.

A spike S was driven into the earth and the pressure to another spike *s*, taken at different points along the street, as indicated by the dots in Fig. 281; the pressures were measured as shown by the figures.

The fault was located exactly under the point where the 30-volt reading was obtained.

Where branches are not available and where the mains are "three-wire" or consist of three cables laid side-by-side, as in most direct current systems, then an ammeter and voltmeter may be used to ascertain the resistance of the defective main up to the fault and compare this with the resistance of a main, preferably of the same size, in good condition.

A current is sent through the ammeter **A** in Fig. 282, the good cable $T_1 T_2$, and the faulty cable $T_5 T_6$. The third cable is only used as a pilot or pressure lead to tap the potential at $T_2 T_4 T_6$, where the cables are joined together. Connecting the voltmeter **V** to top-stud gives V_1, the drop on the good cable; throwing over to bottom stud gives V_2, the drop on the faulty cable from T_6 to f. Then

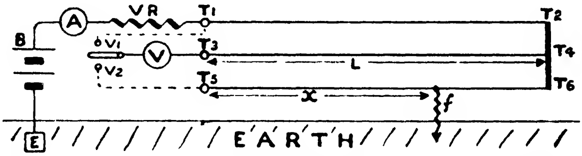


FIG. 282.—LOCALIZING BY AMMETER AND VOLTMETER.

the distance of fault from $T_6 = V_2/V_1$, as a proportion of the length of T_1 to T_2.

A check on this would be to send current through the faulty cable by connecting **A** to T_5 instead of T_1 and take the drop V_3 between T_3 and T_5, with a current A_3. Then if L be the length from T_5 to T_6, the fault-distance x from T_5 would be—

$$x = L \times \frac{V_3}{A_3} \Big/ \frac{V_2}{A_2} + \frac{V_3}{A_3} = \frac{V_3 A_2 L}{V_2 A_3 + V_3 A_2}$$

Ex. (*b*). A fault on a 0·1 sq. in. main 150 yds. long was located by passing $A_1 = A_2 = 8$ amps. through another of same size, using the middle or neutral wire as voltmeter connection. $V_1 =$ 285 mv., $V_2 = 114$ mv.

$$\text{Distance of fault from } T_6 = \frac{114}{285} \times 150 = 60 \text{ yds.}$$

Check test was taken by passing $A_3 = 20$ amps. from T_5 through f, to earth. $V_3 = 428$ mv. Distance of fault from T_5

$$x = \frac{0{\cdot}428 \times 8 \times 150}{(0{\cdot}114 \times 20) + (0{\cdot}428 \times 8)} = 90 \text{ yds.}$$

These add to 150 yd., the length of the main. The fault was a dead-earth.

237. LOOP FAULT TESTS. The fault may not be of such a low resistance as would enable sufficient current to be sent through it to permit of the last method being used. Then a bridge test can often be taken successfully, by forming a loop with another cable in good condition.

In Fig. 283 F is the faulty cable, the earth-fault being indicated at *f*. C_1 is another cable in good condition, a loop being formed by the strapping together, by a conductor of negligible resistance, of T_3 and T_4. A slide wire

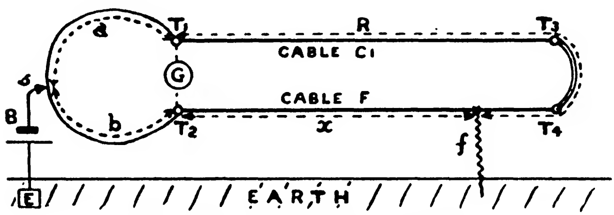


FIG. 283.—MURRAY LOOP TEST.

is connected to T_1 and T_2, the length of this wire being, say, $\frac{1}{36}$th of the total length of the loop T_1 to T_3 and T_4 to T_2. A galvanometer is also joined across T_1 and T_2, while a battery with one pole earthed has the other pole taken to the slider *s*. A bridge is thus formed, with T_2, to *f* as the arm x; the R arm being the resistance of the loop from *f* to T_1.

If *s* be adjusted until balance is attained, then—

$$T_2 \text{ to } f : f \text{ (via } T_4 \text{ and } T_3) \text{ to } T_1 :: T_2 \text{ to } s : s \text{ to } T_1$$
$$\text{or} \quad x : R :: b : a$$

T_2 to T_1 via the slide-wire is a model to a scale of 1 in. per yard of T_2 to T_1 via the looped cables, so that if the balance point for *s* were 25 in. from T_2, then the fault would be 25 yds. from T_2.

It is not necessary to employ a slide-wire in such a loop test any more than in comparing resistances; all that is required is the proportion of b to a, which gives the proportion of x to R, and thus fixes the location of the fault by comparison of the resistance along loop to fault by cable F, to the resistance along remainder of loop by rest of F and C_1. This test is known as the Murray loop method of localization.

Where the loop is made of cables of different sizes the "equivalent length" is calculated for that portion of the loop formed by the good cable, so that it is expressed in terms of the faulty cable, as in the following example.

Ex. (*c*). A 7/20 pilot cable has earthed. A loop was made as in Fig. 284 by another cable of 0·1 sq. in. which happened to be

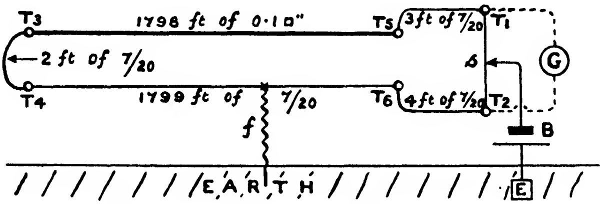


FIG. 284.—EXAMPLE OF MURRAY LOOP.

handy. A copper wire, divided into 1,000 parts, was stretched between the terminals T_1 and T_2.

The loop included 2 ft. of 7/20 cable joining T_3 and T_4; 4 ft. of 7/20 and 3 ft. of 7/20 joining T_2 to T_6 and T_1 to T_5 respectively, making 180 ft. of 7/20 in all.

The rest of the loop was 1,798 ft. of 0·1 sq. in. cable whose resistance was the same as would have been given by 126 ft. of 7/20, so that the loop was equivalent to 1,934 ft. of 7/20.

A test, taken from $T_5 T_6$ end, gave balance at division No. 319 from T_2.

$$\text{Distance of fault from } T_2 = \frac{319}{1000 - 319} \times 1934 = 617 \text{ ft.}$$

$$\text{Deduct length } T_2 \text{ to } T_6 \qquad = 4 \text{ ft.}$$

$$\text{Tested distance of fault from } T_6 \qquad = 613 \text{ ft.}$$

A check test was taken from T_3 T_4 end, *s* balancing at division No. 614 from T_4; then joined up by 2 ft. of wire.

$$\text{Distance of fault from } T_4 = \frac{614}{1000 - 614} \times 1934 = 1188 \text{ ft.}$$

$$\text{Deduct length from } T_3 \text{ to } T_4 \qquad = 2 \text{ ft.}$$

$$\text{Distance of fault from } T_4 \qquad 1186 \text{ ft.}$$

On opening the ground the fault was found to be actually 611 ft. from T_6.

Direct reading fault finders are made with an adjustable contact for T_1 so that the number of divisions between T_1 and T_2 can be selected equal to the number of yards equivalent length of the loop. Then the balance point of *s* on the slide-wire gives the number of yards the fault is distant from T_2.

The diagram of connections of one type of fault finder is given in Fig. 285. The slide-wire 0 – 100 is extended by coils *r*, each equal in resistance to the slide-wire. Four coils are provided at each end of the slide-wire. As depicted the slide-wire comes between 200 and 300 divisions with a total equivalent of 500 divisions, which would be suitable for locating a fault about halfway round the cable loop between T_1 and T_2. The wire alone can be used, or any one or more of the extension coils *r* can be added in series at either end. This is not direct reading, but it permits of a suitable total length, for slide-wire and added resistances, to be selected for any given loop test required.

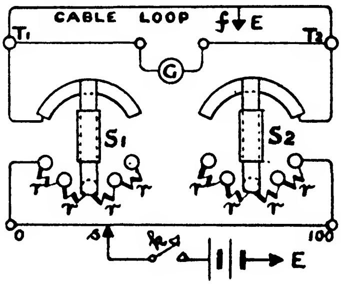


Fig. 285.—Elliott Fault Localizer.

238. INDUCTION METHOD. One end of the faulty main is connected to an induction coil, operated by a small battery, or through an interrupter to a battery, the other pole of which is earthed. The interrupter is merely an instrument for making and breaking current rapidly, causing a pulsating current to flow along the faulty main as far as the fault, then to earth and back to the other side of the battery. This pulsating current is detected by means of a search coil and a telephone receiver. The search coil consists of a large number of turns of fine wire wound on a frame. The operator, carrying the search coil in his hand, walks along the route of the cable. The receiver is connected to the ends of the search coil and the induced current in the search coil causes a tapping or ticking sound in the receiver. At first the tapping sound is loud; as soon as the position of the fault has been reached, it either ceases suddenly or undergoes a marked

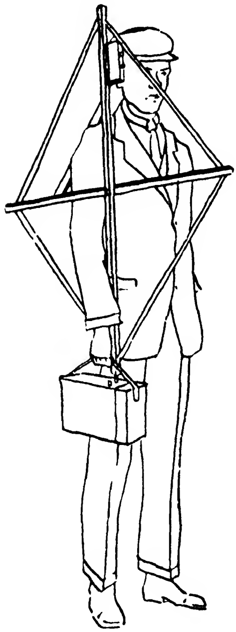


FIG. 286.

SEARCH COIL AND INTERRUPTER BEING CARRIED.

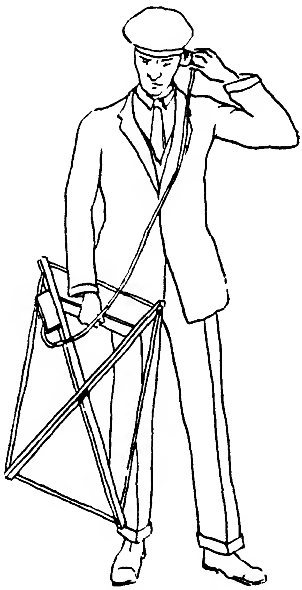


FIG. 287.

SEARCH COIL AND INTERRUPTER IN USE.

change, according to the nature of the fault and of the subsoil in its neighbourhood. The method is simple, and in the majority of cases to which it can be applied the indication is definite.

As a rule, the search coil can only be employed with unarmoured cables, but, by the use of an induction coil giving a series of impulses of great inductive power, it is possible to find faults on armoured cables, and to detect them when they have hundreds of ohms resistance. This method can even be used on live cables by superimposing the pulsating current upon the ordinary supply on the mains. Search and induction coils which give good results in practice are made by Price and Belsham under the name of the Sharman Fault-Detector. Fig. 286 shows the search-coil and interruptor being carried, showing their portability, and Fig. 287 gives an idea of how the operator actually searches for the fault.

239. OPEN CIRCUITS are caused by the ground, in which a cable is laid, moving so as to pull joints apart, or by the + cable on a d.c. system corroding away due to electrolysis. To find such faults the defective section is isolated, and then network boxes, joints and other connections are examined.

When the open-circuit exists on a length, say, of armoured cable, the only test possible is to treat the faulty core as a condenser and to compare the capacity of that length up to the fault with the capacity of another known length of the same cable in good condition. The open-circuited core is charged from a battery and discharged through a ballistic galvanometer and the deflection is noted. The good core, or length of similar cable, is then charged, and discharged through the same galvanometer and the resulting deflection noted. The ratio of the deflection thus obtained gives the proportion of the length of the bad cable up to the fault compared with the length of the good cable.

If all the cores are open-circuited the discharge deflections are taken from each end for one of the cores; their sum is proportional to the length of the cable, so that the fractional distance from each end is given by the ratio of the deflection from each of the ends to the sum of the deflections. As the test is merely a comparison of capacities it is convenient sometimes to use an adjustable standard condenser, and to work out the respective capacities in microfarads.

Ex. (*d*) An open-circuit fault exists on a well-insulated three-core cable which from records at time of laying is known to be 3,120 yards long.

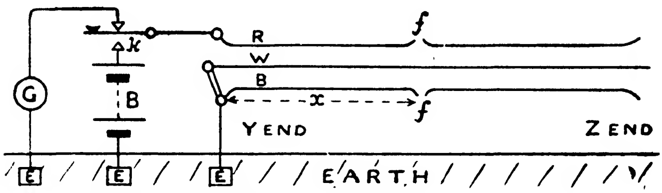


Fig. 288.—Localization of Open-Circuit Fault.

The capacity discharge from the open-circuited conductors was compared with that from the third core, which was not faulty, under the same conditions of charge and discharge, Fig. 288. The battery pressure and actual capacity of the cable per mile did not enter into the test.

Test.	From Y end.	From Z end.
Red core with others earthed	34·5 div.	40·0 div.
White core ,, ,,	73·5 div.	71·5 div.
Blue core ,, ,,	33·5 div.	39·5 div.

$x = \frac{34\cdot5}{73\cdot5} \times 3120 = 1445$ yds. from Y : $x = \frac{39\cdot5}{71\cdot5} \times 3120 =$ 1736 yds. from Z.

From records it was known a joint existed at 1,420 yds. from Y and 1,700 yds. from Z ; this was opened and it was found that two cores had pulled completely apart through mining subsidence.

240. INDICATING INSTRUMENTS are generay employed for the measurement of current, pressure and power in electricity supply practice. There are indirect methods, used principally in standardizing, an account of which will be found in special treatises on testing. In the last chapter the measurement of pressures by the potentiometer has been dealt with.

Readings should always be taken on the upper parts of a scale, so this means that if a reading falls within the lower part another instrument should be obtained. For reasonably accurate work extending over a considerable range there should be at hand a set of instruments, which may conveniently in the case, say, of ammeters, go up in the proportion of 1 to 3 in top-scale reading in something like the following order: ½ amp., 1½ amp., 5 amp., 15 amp., 50 amp., 150 amp., and so on. Then a suitable instrument is available to measure any current without attempting to gauge fractions of a scale-division by the eye.

There are roughly three classes into which measurements may be divided: (*a*) the verification of standards or for the reproduction of substandards from them, and in such cases *extreme accuracy* is of importance; (*b*) the calibration or checking of instruments to be used for testing those in a station, or for ascertaining that consumers' meters are correct, or to be employed on "acceptance tests" of plant delivered by a manufacturer. These must be measurements of *precision*, although not so refined as the first class; (*c*) measurements of a *commercial* character, such as the indication of loads on generators, currents taken by motors or going into secondary batteries on "charge," or the "units" consumed by purchasers of electrical energy. In those cases a tolerance or margin of something like 2½ per cent on either side of absolute accuracy is often permissible. "All truth is relative," and it just depends upon how much it is worth while to spend in attaining precise values; in some cases it pays to eliminate every possible error, in others an approximate value is all that is needed.

241. MOVING-COIL INSTRUMENTS for the measurement of current possess the following *advantages*: (*a*) They are dead-beat. (*b*) They are not subject to hysteresis errors. (*c*) There is very little power lost in the instrument. (*d*) The scale is a uniform one, and the instrument can—in consequence—be employed throughout practically the whole of its range. The *disadvantages* of moving-coil instruments are: (*e*) They can only be used on direct current circuits, as they would be unaffected by an alternating current of normal frequency, which would endeavour to turn the coil both ways at once, and so would not deflect it at all. (*f*) They are subject, in the case of voltmeters and shunted ammeters, to errors due to changes of temperature unless these are corrected or compensated for in some way.

The advantages so far outweigh the disadvantages that this type is generally employed for the measurement of direct currents and pressures in electricity supply. It has to be added that (*g*) moving-coil instruments cost more than the soft-iron type, and thus are considered rather too

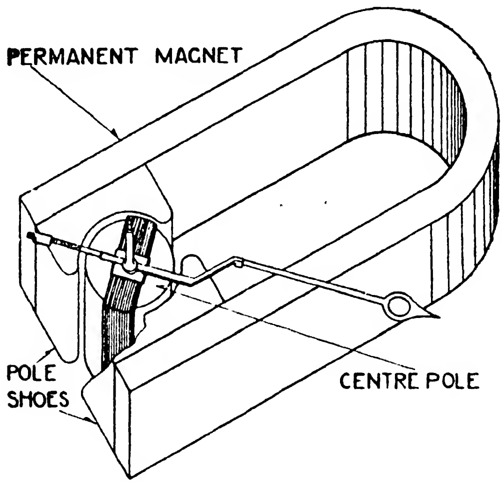


FIG. 289.—PRINCIPLE OF MOVING-COIL INSTRUMENT
(*Record Elec. Co., Ltd.*)

good for the cheapest class of work where rough indications are sufficient. An advantage in certain cases of considerable practical value, is (*h*) that a moving-coil instrument can be given a centre-zero, so that the pointer indicates direction of current by the side of the scale to which it deflects, and the magnitude of the current by the amount of that deflection. A further advantage is (*i*) that by using different shunts, in the case of current measurements, and different multiplying resistances in the case of pressure measurements, the same indicator may be used for a large range of tests.

Moving magnets are not now used as parts of any supply instruments.

242. CELL-TESTERS are small portable voltmeters for the special purpose of measuring the pressure across the terminals of secondary cells. For illustration the Evershed cell-tester, an example of a *sector-pattern* instrument, has been selected.

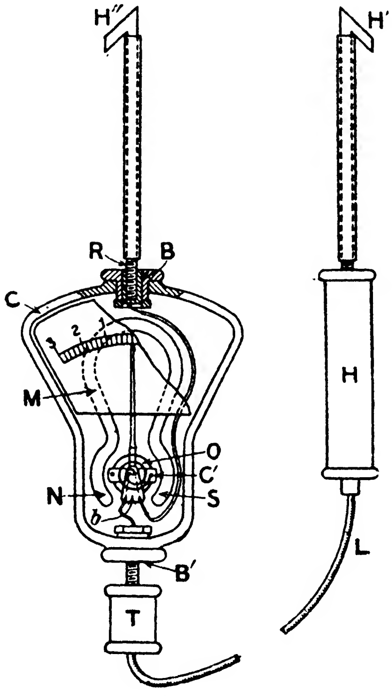


FIG. 290.—EVERSHED CENTRAL-ZERO CELL-TESTER. (Interior view.)

In Fig. 290, **C** is the aluminium-alloy case containing the working parts. The permanent magnet has the curved pole-faces forming its ends so shaped that they are concentric with the fixed soft-iron cylinder **O**, which is carried by a brass support *b* attached to the base of the case. Between the pole-pieces and the cylinder is a small air-gap in which the coil **C′** moves, this coil consisting of a number of turns of fine wire wound upon a light copper frame pivoted between the base of the case and the top of the fixed brass angle-piece *b*. Two spiral hair-springs placed above the coil, one a little above the other, control the movement and lead the current in and out. Only one of these is shown in the figure. The terminal lead from one spring is led to a brass socket insulated from the case by a push B, the brass socket being threaded to receive an ebonite-sleeved metal rod R, which terminates in a hook.

A second rod with a similar hooked end, fixed in an insulating handle H, is connected with the voltmeter by means of a flexible lead L carrying a screwed terminal pin T which screws into the insulated socket B′, the latter being connected inside the case with the terminal lead from the second hairspring.

When making a test, the instrument is grasped in one hand at its narrow end, and the pointed end of the fixed terminal rod is pushed or pulled firmly against one of the cell terminals. The second terminal rod is held in the other hand, and brought into contact with the other terminal of the cell. The pointer then indicates on the dial the voltage of the cell

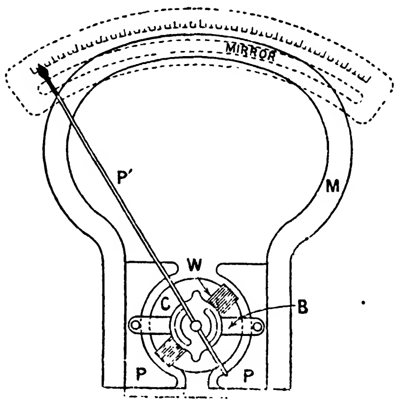


FIG. 291.—PRINCIPLE OF WESTON MOVING-COIL INSTRUMENT.

The dial is provided with a centre zero so that the needle moves either to right or left, it being thus immaterial which terminal rod is connected to the (a particular) pole of the cell.

Three different makes of cell-testers tested gave the following results—

	Resistance.	Maximum reading.	Current taken.
D	97·2ω	3·0 volts	30·9 milli-amps.
E	589·0ω	3·0 ,,	5·09 ,,
F	816·0ω	3·0 ,,	3·68 ,,

243. THE WESTON Electrical Instrument Co., Ltd., make a large number of different sizes of instruments acting on the moving-coil principle These include sensitive and large-dial instruments for the accurate determination of small currents, particularly adapted for use as reference standards in laboratories, and portable instruments with shorter scales for general measurements.

A general view, showing the interior of the indicating portion of a typical form, is given in Fig. 291; while Fig. 292 shows the moving coil and one pole-piece, the permanent magnet and the other pole-piece being removed.

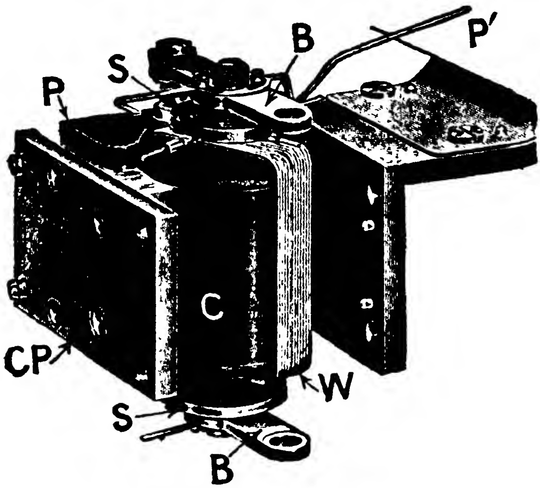


Fig. 292.—Moving Coil of Weston Instrument.

Corresponding parts of the two illustrations are lettered similarly.

The permanent magnet **M**, which is designed so as to give a strong and uniform field, has wrought-iron pole-pieces **P P**, with curved faces concentric with the soft-iron cylinder **C**. The latter is carried by a projection on a gun-metal cross-plate **CP**, fixed across the ends of the pole-pieces. Between the pole-pieces and the cylinder is a very small air-gap, in which the coil **W** moves. This coil consists of a large number of turns of fine wire, wound upon an aluminium frame pivoted between two jewelled bearings, the latter being carried by bridges **B**, **B**, fastened across the pole-pieces. Two spiral hair-springs S, S, one above and one below the coil, serve the double purpose of controlling its movement and of leading the current in and out. In order that temperature errors may be eliminated, the two springs are wound in opposite directions, so that when one is wound up by the rotation of the coil the other one is unwound. A light pointer, P′, of aluminium, is

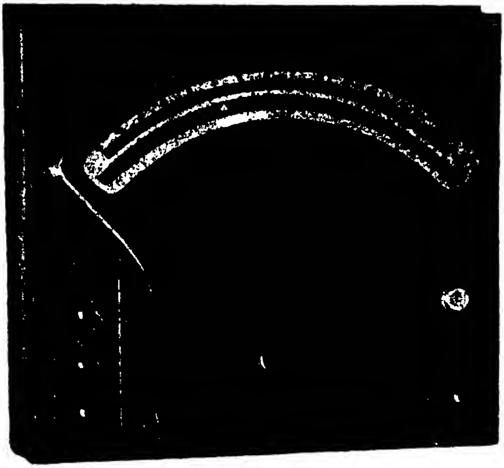


FIG. 293.—LABORATORY TYPE MOVING-COIL INSTRUMENT, WITH LONG SCALE.
(*Weston.*)

attached to the coil, so that the motion of the latter is indicated on a scale, a mirror (Fig. 174) being inserted in a slot in the scale beneath the pointer, in order that parallax error may be avoided in taking the reading. The aluminium frame on which the coil is wound also serves to make the instrument dead-beat, so that the needle comes quickly to rest. Eddy currents are induced in the frame when the coil is in motion, and these currents exercise a braking or damping effect upon the motion of the frame and coil.

The zero position of the coil makes an angle of 45° with a line joining the centres of the pole-pieces. When current passes through the coil, the current-carrying sides of the latter move across their respective portions of the permanent field, in accordance with the rule already given. The deflecting force acts against the controlling force of the springs, the coil coming to rest when the two forces exactly balance each other.

The turning force is proportional to the current in the coil, and the controlling force exercised by the springs is proportional to the amount of turning of the coil. Hence if the turning force be doubled by sending double a given current through the moving coil, the coil moves until the new deflection is double that obtained with the given current, when the controlling force will likewise be doubled. Thus the deflection is directly proportional to the current; and the divisions on the scale of the instrument are consequently uniform throughout the whole range.

Later types vary in their details, but the principle can be followed from the description given.

Milli-ammeters are not provided with shunts, as the coil is capable of carrying the whole of the current. In the case of an ammeter, the construction of which is otherwise exactly similar, the moving coil is connected across the potential terminals of a shunt of low resistance, so that only a small portion of the main current passes through the coil.

In a voltmeter a high non-inductive resistance is inserted in series with the moving coil, as the resistance of the wire on the latter cannot be made very great. The resistance of a voltmeter reading up to 150 volts is about 15,000 ohms.

A portable voltmeter is often given a double scale for two different ranges, and a diagram of the connections within such an instrument is given in Fig. 294. The positive terminal on the right-hand side is common to both ranges; while one or other of those on the left-hand side is used for the negative terminal, according to the pressure to be measured. If the maximum readings are, say, 15 and 150 volts respectively; then one of the left-hand terminals is marked 15, and is connected within the instrument to the resistance in series with the moving coil at a point *p*, such that the resistance between the + terminal and the 15-volt terminal is $\frac{1}{10}$th of that between the + terminal and the 150-volt terminal.

The push-button actuates a contact key K which closes the voltmeter circuit when a reading is taken. This key can be permanently closed by depressing the button and giving it a quarter turn, so as to lock it down.

A common figure for the resistance of a moving-coil

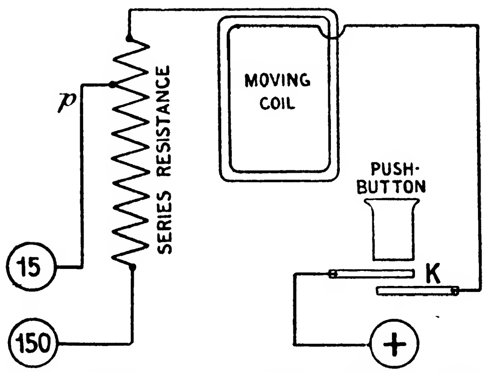


FIG. 294.—CONNECTIONS OF MOVING-COIL VOLTMETER.

voltmeter is 100 ohms per volt for which the scale is graduated. The resistance of a set-up or suppressed-zero 10-inch dial instrument with vertical scale, reading to 150 volts, is in the order of 8,300 ohms.

244. VOLT-AMMETERS. A single indicator, consisting of a moving-coil milli-ammeter, can be employed as an ammeter for various ranges by the use of different shunts to carry the main current; and as a voltmeter, by having multiplying resistances added in series with the instrument. A sub-standard indicator has a scale graduated into 100 divisions, and if properly used its readings may be relied upon to within 0·5 per cent. Being provided with a temperature compensating device its indications are independent of temperature variations. Three instruments of different makes have the following constants—

	Resistance between terminals.	For full-scale deflection. Current.	Pressure.
G	1·5 ohms	50 milli-amps.	75 milli-volts
H	10·0 ,,	4·5 ,,	45 ,,
I	100·0 ,,	0·125 ,,	12·5 ,,

As an ammeter, instrument *G* is provided with five shunts giving full scale deflection for the following currents—

Resistance of shunt, ohms. . . .	0·075	0·015	0·0075	0·0006	0·0003
Max. current, amps.	1	5	10	125	250

Instrument *H* is particularly useful, as it has a very carefully adjusted resistance between its terminals, so can be employed in many ways with ordinary boxes of coils and known low resistances. Low resistance milli-voltmeters are always provided with a set of flexible connecting leads and the instrument is calibrated with these in circuit. When such a milli-voltmeter is used to measure the potential drop across a low resistance shunt carrying the main current, care must be taken to see that the proper leads join up the instrument to the shunt.

A moving-coil voltmeter is really an ammeter which measures the current through a fixed high resistance, the full-scale deflection being usually given with 15 milli-amperes; while an ammeter of the same class is an instrument indicating the milli-volts across the potential terminals of a low resistance shunt connected in the main circuit, the pointer usually going to the top of the scale with a potential drop of 75 milli-volts.

In this case, if a switch is used to connect different shunts to one indicating instrument, it must have a contact of low and constant resistance. If the contact-resistance caused a drop of 1 milli-volt, the result would be an error in reading of 1·3 per cent, while if the contact resistance varied, the error would be an unknown quantity.

A switch specially designed to meet these conditions is illustrated in Fig. 295. The contact is made by a laminated brush, carefully bedded, with each stud tested for contact-resistance.

245. CIRSCALE INSTRUMENTS have a circular scale, and by a special disposition of the magnet poles and moving coil the pointer deflects through an arc of about 300°. This is an advantage as each scale division is about three times as large as on the ordinary form of scale. The instruments made by the Record Electrical Co., Ltd., have scale ranging from 2¾ in. to 16 in. dial diameters, the scale-lengths being more than twice the diameter. This is indicated by Fig. 296, which is an external view of a compact form of portable testing set, giving two ranges of current and three of pressure, according to the terminals connected to the circuit. Normally amperes are indicated; to read volts the key in the centre is depressed.

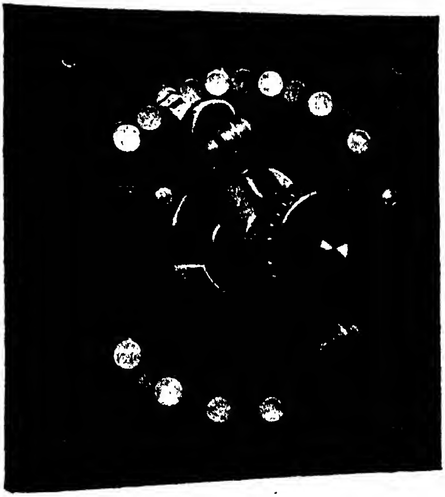


FIG. 295.—SELECTOR MULTIPLE-POINT SWITCH FOR USE WITH D.C. AMMETERS.
(Record Electrical Co., Ltd.)

The long scale is due to the use of flat circular pole shoes orming wo air-gaps magnetically in parallel. The strong working field results in freedom from interference from external magnetic influences, while the low reluctance of the magnetic circuit reduces magnetic leakage to a minimum. Fig. 297 shows a switchboard instrument with the case removed, while Fig. 298 gives a view of the permanent magnet, like an elongated *C*.

To the magnet the pole pieces are secured. The pole round which the coil—also shown in Fig. 298—swings is circular. This pole is sandwiched between the outer poles, leaving an air-gap on both sides, so that the flux from the first pole divides, half of it traversing the upper air-gap, and the other half the lower air-gap, but the flux in both these gaps is cut by the conductors on the moving coil.

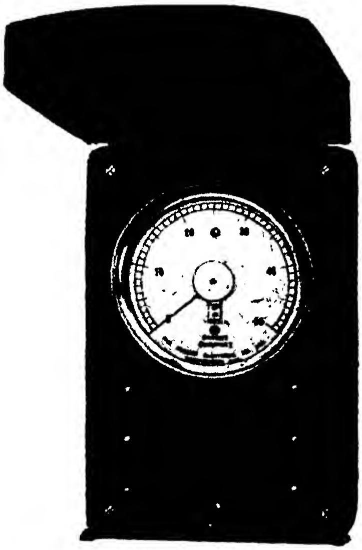


FIG. 296.—MINIATURE CIRSCALE COMBINED TESTING SET. (*Record Electrical Co., Ltd.*)

246. STATION INSTRUMENTS of the moving-coil type are made both with and without illuminated dials. A large dial voltmeter has been selected for description.

This is shown in Fig. 299 with cover and dial removed. The moving coil **C**, Fig 300, is wound on an aluminium frame, and it embraces one of two curved soft-iron pole-pieces clamped beneath the poles of a compound permanent magnet.

N N and *S S* are the extremities of the poles of the permanent magnet; and *ssss* and *nnnn* the curved soft-iron pole-pieces attached thereto. The bottom half of the coil is chiefly acted upon, this being in the dense field between the two pole-pieces. When current passes through the coil, those conductors forming the bottom half will travel along the interpolar field, and those forming the top half will also help in this movement.

The moving system, pivoted on the axis **A**, carries an aluminium pointer, and is controlled by two spiral springs of phosphor bronze, which also conduct the current into

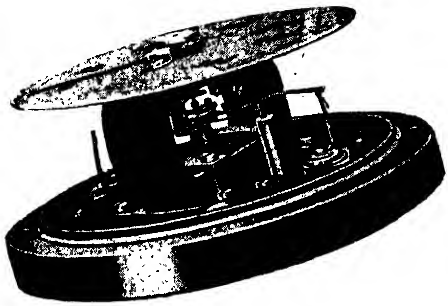


Fig. 297.—Cirscale Switchboard Instrument with Cover Removed.
(Record Elec. Co., Ltd.)

and out from the coil. These springs are fitted opposite ways, so that one is unwound and the other wound up when the coil is deflected from its zero position. The tendency of these springs to regain their normal positions

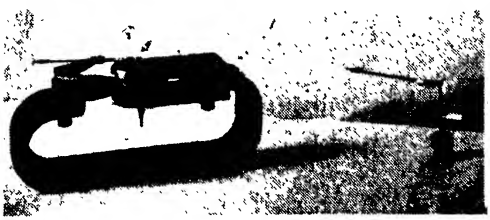


Fig. 298.—Magnet, Pole-Pieces and Moving Coil of Cirscale Instrument.

brings the needle back to zero. The springs may be seen at *S*. *R R* are light rubber buffers mounted on wires, these serving to arrest the movement of the pointer at either end of the scale.

As is usual with moving-coil instruments, owing to the small resistance that can be got on the coil itself, extra resistance is included in the circuit, this being wound on two bobbins, *B B*. The terminals of such apparatus usually take the form of screwed brass stems, suitably insulated and rigidly secured, which are brought through the back of the instrument case for connection to the outside circuit. Lamps for illuminating the dial are external to the instrument case.

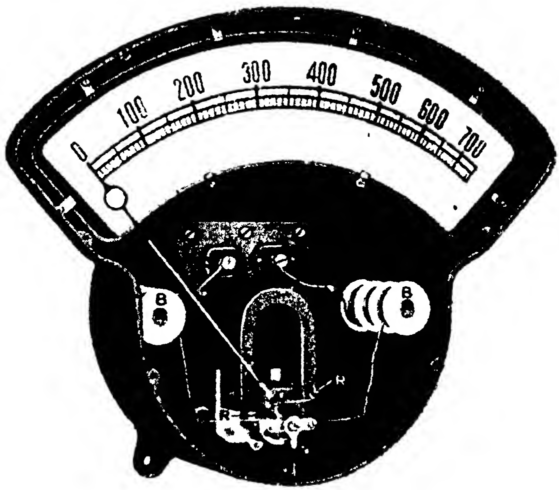


Fig. 299.—Interior of Moving-Coil Instrument.
(Metropolitan-Vickers.)

The internal arrangement of an ammeter of this type is exactly as shown, the scale, however, being graduated in amperes, and the instrument connected up to a shunt.

Instruments with the pointer moving from left to right take up a good deal of room. To save space the movement is sometimes arranged vertically, and where two pressures have to be measured simultaneously—as in the paralleling of dynamos on station bus-bars—duplex voltmeters have two separate movements in the same case, as in Fig. 301.

247. SOFT-IRON INSTRUMENTS are to be found where first cost is the factor determining selection. (*a*) They are cheap, and quite good enough where accuracy is relatively unimportant. Very often they are ampere-gauges and volt-indicators rather than ammeters and voltmeters.

The other disadvantages and advantages of instruments of the **moving-iron type** are as follows: (*b*) When used on direct-current circuits with a varying voltage or current

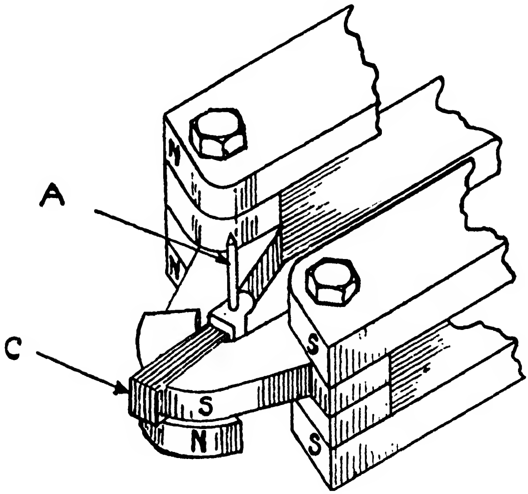


FIG. 300.—PRINCIPLE OF MOVING-COIL INSTRUMENT.
(*Metropolitan-Vickers.*)

there are often errors due to residual magnetism ; and some instruments of this class will not give the same readings with increasing voltage or current as they will with diminishing voltage or current. (*c*) Their readings are easily disturbed by external magnets, or by current-carrying conductors near them. The error due to this cause may be considerable, and is liable to occur both on direct and alternating current circuits. (*d*) They are not very dead-beat, unless special means are employed to make them so. (*e*) The lower parts of the scales are very cramped, and divisions are not equal. (*f*) On the other hand, moving-iron instruments possess the advantage of being available for both direct and alternating currents. Any given moving-iron instrument, however, must be calibrated either for direct or for alternating current; and cannot be used with correctness on either kind of circuit at will. The same pointer sometimes has two scales, one graduated on direct current, and the other on alternating current of a stated frequency.

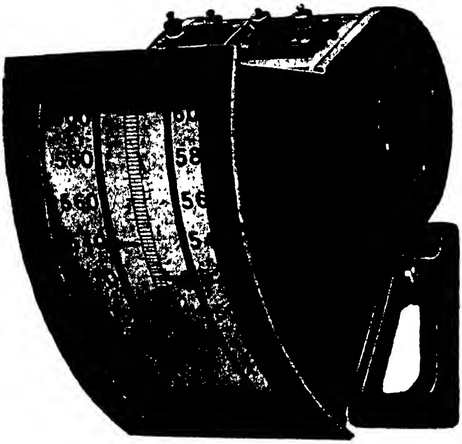


FIG. 301.—DUPLEX PARALLELING VOLTMETER.
(*Evershed and Vignoles.*)

The control is usually gravity, as will be seen from the examples illustrated. The magnetic effect may be either attraction or repulsion. The simplest form of instrument depending on attraction is a core, say like a knitting needle but made of soft iron, which is hung at one end of a beam, and is attracted into a solenoid, the other end of the beam being balanced by a counter-poise. Alternatively the soft-iron rod may be hung from a spring balance, as in Fig. 61. Variations on this are to pivot a half-circle of iron in front of a solenoid, when the iron rotates so as to enter the solenoid and thereby strengthen the field.

The internal field of a solenoid midway between its ends is strongest at the centre (axis) of the coil; but towards the ends, where the lines begin to leak out, the field is stronger at the sides than in the centre. Consequently, a piece of iron reaching the whole length of a short coil moves to one side, while a short piece placed midway between the ends of a coil tends to move towards the centre thereof.

The moving part of an instrument employing attraction in the way just described is depicted in Fig. 302, where **S** is the spindle, **P** the pointer, and **A** an armature. The latter consists of a strip of soft iron fixed along the spindle and extending the whole length of the coil, the spindle of the instrument being pivoted considerably above the axis of the coil.

When a current is sent through the coil, the armature **A** will be drawn upwards towards the side of the coil, the pointer moving round in the direction shown by the curved arrow. This movement will be against the force of gravity acting on the small adjustable counterweight **C**; the deflections, therefore, being proportional to the strength of the current, i.e. to the amperes or the volts—according to the winding of the instrument.

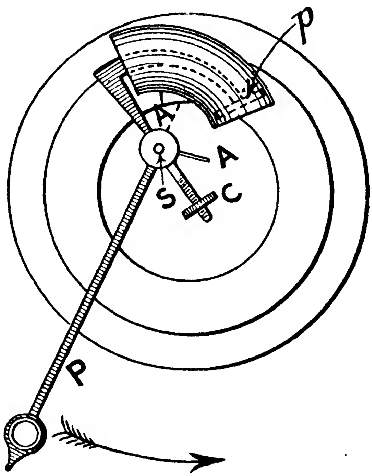


FIG. 302.—PRINCIPLE OF MOVING-IRON INSTRUMENTS.

The moving portion is rendered more or less dead-beat by a dash-pot action formed by a little piston (carried by the upper part of the moving system) working backwards and forwards in a curved tube closed at one end. The piston prevents the movement being too violent or unsteady, but the air-damping does not affect the ultimate position taken up by the armature.

The portion, called the "plug," of a type of instrument where the field is altered by fixed pieces of iron in the interior of the solenoid is shown in Fig. 303, where **N** is the needle fixed to an axle pivoted in agate or jewelled bearings, C the counterpoise, A the soft-iron armature fixed to the axle, P the brass case or "plug," which is open at O, and S a peculiarly-shaped soft-iron sleeve which fits on to P, but is shown apart to allow the interior of the plug to be seen. The armature A is more clearly depicted in Fig. 304, together with the axle N and C. A section across the "plug" showing the sleeve S in place,

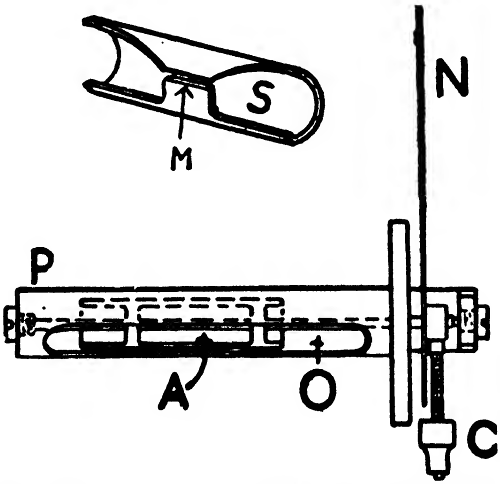


FIG. 303.—"PLUG" OF SOFT-IRON INSTRUMENT.

and its position relative to the armature A when the latter is at zero, is given in Fig. 305.

S offers an irregular path to the lines of force (due to the current) which pass from end to end of the coil; and the free magnetism at and about the point M is stronger than elsewhere. To this region A is attracted against the gravitating force of C. The zero position of A is shown in Fig. 305, C (represented by a dotted line) being heavier than A. The amount of the attraction between A and M depends, of course, on the current passing through the coil.

Fig. 306 gives a plan of a moving-iron ammeter for large currents, with the cover, "plug" and dial removed. The coil **C** is of thick insulated cable, the ends of which are soldered in the terminal sockets **TS TS**, which pass through the base, but are insulated therefrom by ebonite (shown black). The hollow of the coil is at *h*, and it is here that the plug is inserted. This winding is typical of all instruments where the main current is taken through the coil.

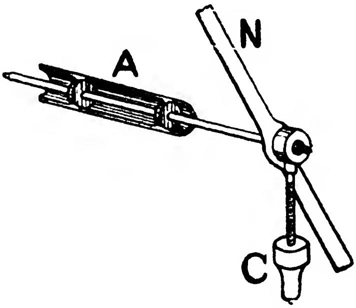


Fig. 304.—Armature and Needle.

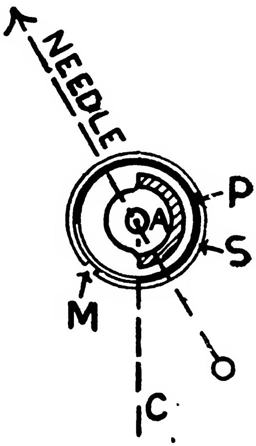


Fig. 305.—Section Across "Plug."

The working part or "plug" of a soft-iron instrument is usually easily removed. The plug of one depending on the repulsion between fixed and moving parts, is shown in perspective in Fig. 307, and in part section in Fig. 308. Fixed to the axle *a*, in the relative positions there shown, are two armatures **A** and **A′**, built up of thin pieces of soft sheet iron; **A′** being less than half the length of and much thinner than **A**. Part of the framework in which the moving part is pivoted consists of a brass tube **B**, which is tightly packed with a number of soft-iron wires **W**. The dotted line *d* indicates the hollow of the coil.

When a current passes round the coil, **B** repels **A**, and the needle moves over to the right. As **A** moves away from **B**, **A′** is brought round towards **B**, against the slight

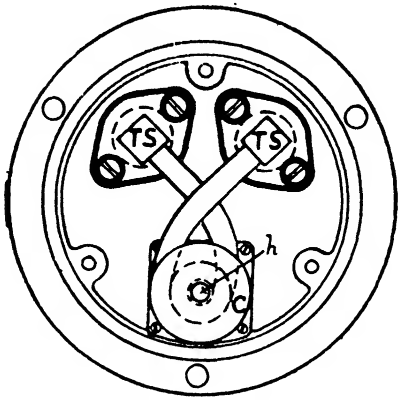


Fig. 306.—Coil and Base of Ammeter.

but increasing repulsion which exists between them. The travel of the needle is thus retarded by this repulsion, as well as by the force of gravity tending to pull **A** down-

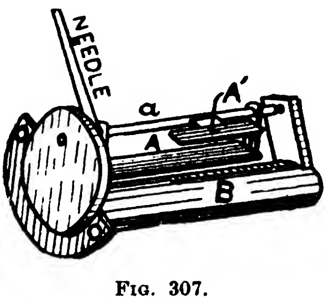


Fig. 307.

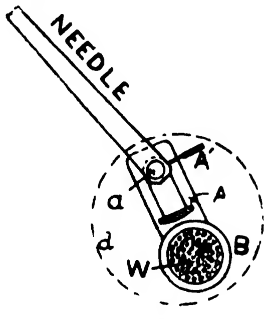


Fig. 308.

wards. This action will be understood from Fig. 309, where a sectional plan of the coil is given, and **W A** and **A′** are shown. Suppose a direct current be flowing round the coil, then one end of W A and A′ will be north, and the other south; thus repulsion will be set up between

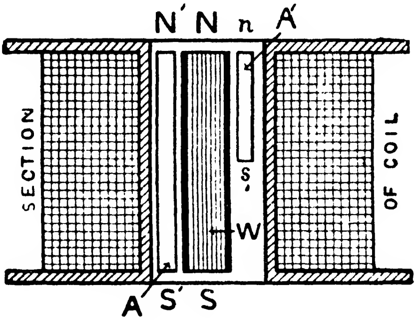


FIG. 309.—SECTION OF SOFT-IRON INSTRUMENT.

N N′ and *n*; and between S S′ and *s*; but the repulsion between W and A will clearly be greater than that between W and A′, and the needle will move over the scale.

FIG. 310.—EXTERNAL VIEW OF AMMETER.

The iron parts being well laminated, such an instrument may be used with alternating currents.

Fig. 310 shows the exterior and Fig. 311 the interior view of an ammeter, of a type where repulsion takes place between fixed and movable pieces of iron, both being magnetized by the solenoidal winding. The moving part is shown in Fig. 312, where S is the spindle. Fig. 311 shows the moving portion in the position of rest.

The magnetizing coil is wound on a bobbin C. Along the inside of the tunnel is fixed a soft-iron strip $F.I.$

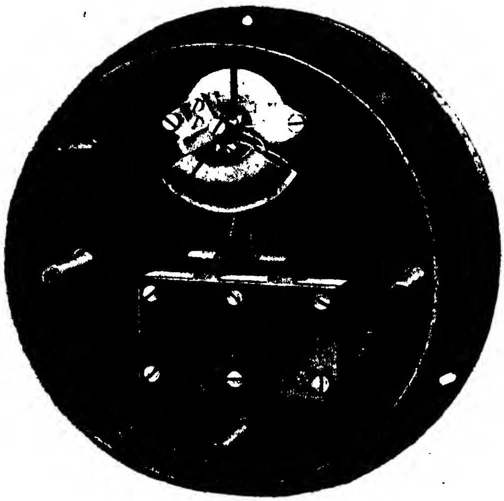


Fig. 311.—Internal View of Soft-iron Ammeter. (*Metropolitan-Vickers.*)

Through the centre of the tunnel a light steel shaft passes, carrying a similar strip of iron $M\,I$, a pointer P, an arm carrying the piston p operating in a tubular dash-pot, and three arms with adjustable weights for balancing. The steel shaft is carefully pointed and hardened, and is carried in sapphire jewels with conical depressions. For most purposes the movement is controlled by gravity but, when required for use in positions other than the vertical, spring control is fitted.

The passage of a current through the magnetizing coil magnetizes the two irons and, as similar poles are adjacent, the moving iron is repelled by the fixed one roughly in proportion to the current. The terminals consist of stiff copper straps brought out through a sealed opening at the back of the case ; front connections can be provided in most instances if desired. Such instruments are suitable for use on a.c. or on d.c. circuits ; the bobbin on

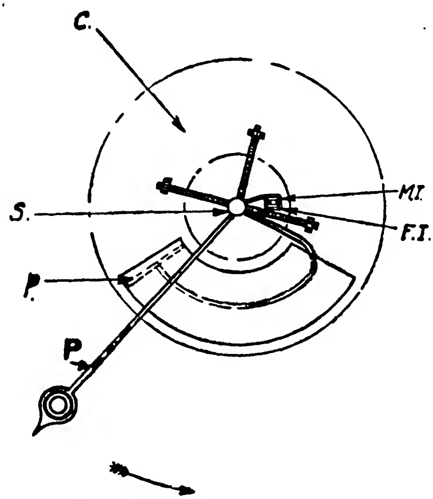


Fig. 312.—Working Part of Soft-iron Instrument.
(*Metropolitan-Vickers.*)

which the coil is wound has a gap, or being cut right through at one point to prevent induced currents being set up and circulating in it.

Data of Some Typical Moving-iron Instruments.

	Max. Current.	Resistance.	Impedance on 100 ~
Ammeters.	0·5 amperes.	5·6 ohms.	11·6 apparent ohms.
	1·0 ,,	2·35 ,,	4·15 ,, ,,
	3·0 ,,	0·15 ,,	0·26 ,, ,,
	5·0 ,,	0·033 ,,	0·078 ,, ,,
	20·0 ,,	0·0071 ,,	0·009 ,, ,,
Voltmeters.	25 volts.	77·5 ,,	91·0 ,, ,,
	120 ,,	2720·0 ,,	2940·0 ,, ,,
	250 ,,	8000·0 ,,	8400·0 ,, ,,

248. DYNAMOMETER INSTRUMENTS are of two classes: those which require the employment of a "constant" to reduce their indications to amperes, and those which read directly. (*a*) They will read accurately on either direct-current or alternating-current circuits with the same scale; the same instrument may be used on either

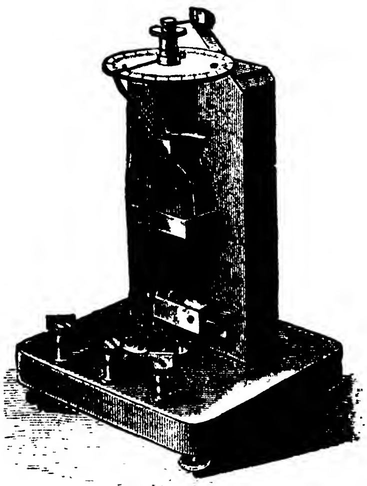


FIG. 313.—SIEMENS ELECTRO DYNAMOMETER.

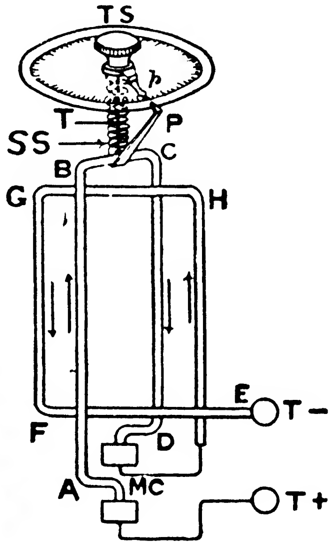


FIG. 314.—DIAGRAM OF ELECTRO-DYNAMOMETER.

kind at will without readjustment. (*b*) As a dynamometer instrument contains no iron, it is independent of variation of the wave-form and frequency of an alternating current. (*c*) The sensibility of the instrument may be temporarily affected by the near presence of strong external magnetic fields.

The Siemens dynamometer is of great interest as being a pioneer instrument, and as illustrating a principle which, with various modifications, has been adopted in later instruments by many makers. The Siemens in its original form is still used in test-rooms for the checking of consumers' meters, where its ability to measure either direct or alternating currents of different frequency is a point in its favour. It is really a species of ammeter, depending for its action upon the mutual attraction or repulsion which takes place between adjacent parts of a circuit.

The *electro-dynamometer* is illustrated in Fig. 313, where it will be seen that it is constructed with three coils of wire, two of which (each consisting of several turns) are fixed; while the other, which encloses the fixed coils, and has very few turns (sometimes only one), is free to rotate about a vertical axis.

Fig. 314 illustrates the action of the instrument. The moving coil A B C D is suspended by a thread T and helical spring SS from a thumb-screw TS; and its lower ends dip in mercury cups MC. E F G H is one of the fixed coils; and both moving and fixed coils are represented by one turn. Only one of the fixed coils and two terminals are represented, for simplicity's sake. The coils are connected up in series, and, when at rest, the movable coil is at right angles with the fixed coil.

The two fixed coils are of a different number of turns, of thick and thin wire respectively, and they admit of two ranges of measurements being made with one instrument, the thin-wire coil being used with small currents and the thick-wire coil with large currents. The swinging coil can be connected in series with either of the fixed coils, according to the terminals used. Fig. 315 illustrates the connections of the instrument. Here *MT* is the middle terminal in Fig. 313, this being connected with the lower mercury cup *MC*. The terminal *LT* (the left-hand one in Fig. 313) is joined up to the thick-wire coil *F*, and the terminal *RT* (the right-hand one in Fig. 313) to the thin-wire coil *F'*. The other ends of both fixed coils are connected with the upper mercury cup *MC'*. One conductor from the outer circuit is always joined-up with the terminal *MT*, and the other with either *RT* or *LT*, according as the thin or thick fixed coil is required.

When the current to be measured passes through both coils, the moving one tends to turn against the tension of the helical spring, so as to place its plane parallel with the plane of the fixed coil; there being repulsion between *GF* and *BA* and between *CD* and *H*, and attraction between *BA* and *H* and between *CD* and *GF*. When the coil is deflected by the passage of a current, the thumb-screw *TS* at the top of the instrument, which is connected with the helical spring *SS*, is turned in the direction opposite to that of the movement of the coil, until the tension of the spring acting against the force due to the current brings the coil and its pointer *P* back to zero, that is to say, the position where the moving coil is at right angles

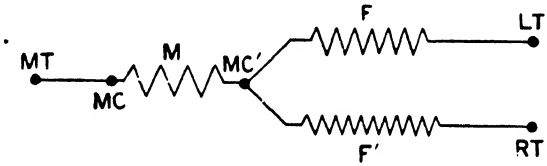


FIG. 315.—CONNECTIONS OF ELECTRO-DYNAMOMETER.

with the fixed coils. The amount of this turning is indicated on the circular horizontal scale by the pointer *p* fixed to the milled head.

When the coil has been brought back to zero, *the current is proportional to the square root of the angle through which the spring has been twisted.* The force of torsion of the spring is proportional to the angle of torsion, i.e. to the amount it has been turned. The force of the current in turning the coil is proportional to the square of the current. Consequently the current is proportional to the square root of the angle of torsion of the spring as indicated on the scale.

The instrument must be *calibrated*, that is to say, some known current C must be passed through the apparatus and the deflection θ noted. Then $C/\sqrt{\theta}$ is the *constant* k of the instrument, and the current value for any other deflection $= k \times \sqrt{\text{deflection}}$. The makers furnish a table giving the square roots of a large number of deflections and the current values equivalent to them.

Data from the tables supplied with two instruments are given below. It will be seen that this pair of dynamometers provide a range of from the fraction of an ampere to over five hundred amperes.

	Instrument A.		Instrument B.	
	Range 0·195 to 20 amperes.		Range 9·14 to 546 amperes.	
	Constant = 0·195 and = 1·0		Constant = 9·14 and = 27·3.	
Div. on scale.	Thin coil.	Thick coil.	Thin coil.	Thick coil.
5	0·437 amps.	2·24 amps.	20·4 amps.	61·0 amps.
25	0·977 ,,	5·0 ,,	45·7 ,,	136·0 ,,
100	1·950 ,,	10·0 ,,	91·4 ,,	273·0 ,,
400	3·70 ,,	20·0 ,,	183·0 ,,	546·0 ,,

249. KELVIN BALANCES are adapted to the measurement of both direct and alternating currents, and are made in various ranges—

(i) Centi-ampere balances, from 0·01 to 1 ampere.
(ii) Deci-ampere balances, from 0·1 to 10 amperes.
(iii) Deka-ampere balances, from 1 to 100 amperes.
(iv) Hekto-ampere balances, from 6 to 660 amperes.
(v) Kilo-ampere balances, from 10 to 1000 amperes.

The principle of each size of balance is the same, but the construction varies according to the range of the instrument. For description the deka-ampere balance is selected. Its action depends upon the mutual forces of attraction and repulsion between movable and fixed portions of an electric circuit. In the electric balance the parts of the circuit which thus react on one another are circular; and the movable part of the instrument may be compared with a balanced beam, with a horizontal coil fixed at each extremity. Above and below these movable coils are fixed coils; and all the coils carry current in such directions that the beam (and its coils) tends to be tilted up on one side, and down on the other.

This arrangement will be grasped from Fig. 316, where

MC MC are the two movable coils, and FC FC, etc., the four fixed coils.

The balance arm which carries the movable coils, and which is not shown in Fig. 316, has also a scale *S′* fixed to it, the edge of which is turned up so as to form a rail on which the weight W slides. The whole beam is supported on two sets of ligaments L L′, of fine copper wire, which also serve to conduct the current into and out from the movable coils.

The current to be measured is passed through the whole

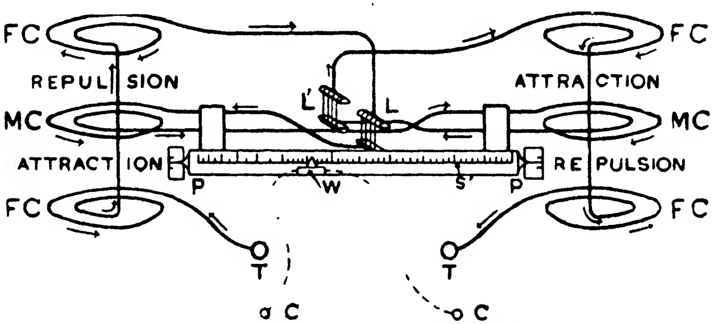


Fig. 316.—Diagram of Current Balance.

of the coils in series, in such a direction that the right-hand movable coil is forced upwards by the repulsion of the bottom fixed coil and the attraction of the top one; while the left-hand movable coil is drawn downwards by the attraction of the bottom coil assisted by the repulsion of the top one. As a consequence, the beam is tilted over. The sliding weight W is then slid along by the slider S until the beam once more lies in a horizontal position, this being indicated by the little pointers P P at each end. The weight is slid along either way by pulling the cords C C. In Fig. 316, for simplicity's sake, C C are represented as fixed to W, but in reality they are attached to the slider S, which in turn moves W.

The number of turns and size of conductor on the coils of course depend upon the range of the instrument. The terminals are at the back of the apparatus, and the connections to the circuit are made by means of flexible leads.

An illustration of the balance is given in Fig. 317 (on folder at end of chapter). When balances are intended for use with alternating currents some modifications are necessary, particularly if the currents are large. The conductors, instead of being made up of bars or strips, are composed of stranded copper, so that the current tends to divide uniformly across the cross-section of the conductor, and the supports and other parts adjacent to the current carrying circuit are made of slate or some material in which eddy currents cannot be induced.

Balances of this type are employed in meter-testing rooms and other places where accuracy is essential, and the apparatus will be handled by skilled observers. There are so many appliances employed in electrical work which depend on the dynamometric principle that a clear understanding of the action of the balance is certainly desirable.

250. STANDARD BALANCE. The ampere-standard, made for the Board of Trade and now in the National Physical Laboratory, is the embodiment of the legal ampere. It consists of one movable coil, hung between two fixed coils, one above and the other below. The coil is suspended from one end of the beam of what is similar to a large chemical balance. The other end carries a scale-pan, and a second scale-pan is fixed above the movable coil. In series with the movable coil is a reversing switch.

The counter-poise weight used exactly counter-balances the attraction of the lower coil, and the repulsion of the upper coil, upon the movable coil when the current is flowing through it in one direction, and the weight is in the opposite scale-pan. To eliminate the possibility of error due to an extraneous field, a second measurement is made with the current in the movable coil reversed, and the weight in the scale-pan above it. If the current still flowing be one ampere, the beam will remain in balance.

This instrument was constructed on the principle of the balance, in which, by the proper disposition of the conductors, forces of attraction and repulsion are produced, which depend upon the current passing, and are balanced by known weights. The legal description of the standard of electrical current is—a standard denominated one ampere, being the current which is passing in and through the coils of wire forming part of the instrument marked "Board of Trade Ampere Standard verified 1894 and 1909," when on reversing the current in the fixed coils the change in the forces acting on the suspended coil in its sighted position is exactly balanced by the force exerted by gravity in Westminster upon the iridio-platinum weight marked *A*, and forming part of the said instrument.

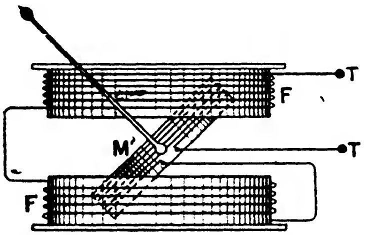


Fig. 318.—Diagram of Dynamometer Voltmeter.

251. DYNAMOMETER VOLTMETER. The theory and action of this instrument are similar to those of the electro-dynamometer already dealt with. It will be obvious that it is suitable for use on both direct and alternating current circuits. The appearance of a portable voltmeter of this class, as made by the Weston Instrument Co., Ltd., is similar to the illustration given later of a Weston Wattmeter, except that the current terminals shown in that figure are omitted.

From a diagram of the windings in Fig. 318 it will be seen that such an instrument consists of two fixed fine-wire coils F F, and one movable coil M; the latter being of smaller diameter than the two former, and pivoted between them. When no current is passing, two spiral springs hold M so that its plane is at an angle of about 45° with that of the fixed coils. When a current passes the movable coil tends to turn so that its axis coincides with that of the fixed coils. The amount of this turning, which is against the force of the spiral springs, depends on the strength of the current, that is to say, on the p.d. applied at the terminals T T.

In Fig. 319, which gives a perspective view of a portion of the interior of one form in which the instrument was made, **S** is one of the spiral springs which control the movement of **M**. The second fixed coil is removed to enable it to be seen. In this figure the instrument is represented as lying on its face, and only a small portion of the

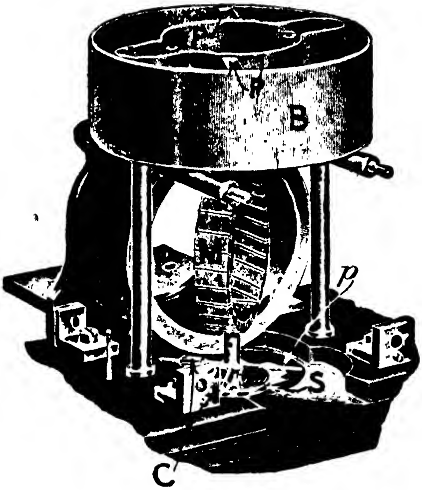


FIG. 319.—PORTION OF INTERIOR OF DYNAMOMETER VOLTMETER.

pointer stem *p* is shown. This stem consists of a light aluminium tube, and the cross arms by means of which it is balanced can be seen at **C**. In later patterns the pointer is a system of trussed aluminium tubes.

In order to damp the motion and any minor vibrations of the moving system, and so render the instrument dead-beat, the coil **M** has attached to it a light aluminium vane (not shown) which is provided with two pistons **P P**. These vanes move in an air-damp box **B**, the bottom of which is removed to enable the interior to be seen. When the coil M is deflected, the vane and pistons move with it, but the clearance allowed in the damper box is so small that the motion is retarded, and the instrument rendered dead-beat.

Dynamometer instruments necessarily cannot be made of very low resistance, and are therefore not suitable for use, in connection with shunts, as ammeters. The difficulty would be to get sufficient deflecting force with the small p.d. that would be available.

252. HOT-WIRE INSTRUMENTS utilize the heating power of the current for indicating its value, or the value of the pressure p.d. giving rise to it.

Such instruments, which are called hot-wire ammeters or voltmeters, according as they have been calibrated to indicate current or pressure, may be used on either direct-current or alternating-current circuits of any frequency, without modification or adjustment, as the heating effect is quite independent of the direction of the current. Other advantages of this type of instrument are its very small inductance, which is due to the absence of solenoids and iron in the construction ; and it is absolutely dead-beat.

Instruments of the *hot-wire type* are not influenced by external magnetic fields, and can easily be constructed so as to be free from temperature errors. They have scales rather " close " at the lower part of the range, and more open at the higher part, because the heating effect is proportional to the square of the current. For some purposes this is a disadvantage, for others it is a distinct advantage. They are somewhat sluggish in action, owing to the time taken by the measuring-wire in attaining its final temperature corresponding to the current under measurement. They are liable to burn out, or the working wire melts, if over-volted. Compared with other types, they absorb a good deal of energy. Thus they cannot be used satisfactorily across circuits of high resistance. They have a distinct place, however, in practical work. For example, they are serviceable on rectified circuits to test the p.d. across the terminals of arc lamps, after being calibrated *either* on d.c. or a.c. They make excellent "pilot voltmeters," being adjusted after connection to the pilot leads on which they are to be used.

Galvanometers for Alternating-current work have been made on the hot-wire principle. The plug **P** (Fig. 320) fits into a socket on a supporting stand. The two wires **W W′** have the same rate of expansion, so that the position of the mirror **M** is not affected by atmospheric changes of temperature. The front wire **W** does not carry the current, it being insulated at its lower end. At its middle it carries a small spindle **S** to which **M** is attached. On this spindle and below **M** are wound a few turns of fine silk thread **S′**, one end of which is connected to the spindle, while the free end is attached to the current-carrying wire **W′** by a wire loop **L**. A tightening screw (torsion head) **TS** enables a twist to be given to the front wire, so that it pulls on **W′**. A current passing through the latter heats it more or less, and enables it to "give" to this pull, thus allowing the mirror of the reflecting system to turn slightly.

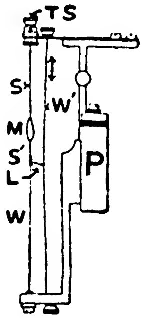


FIG. 320. HOLDEN HOT-WIRE GALVANOMETER.

Instruments acting on the hot-wire principle have been used for measuring small p.d.'s, but have now dropped out of use, one reason being that their action was too slow. A description of construction, however, leads up to an understanding of larger instruments of the same class. In Fig. 321 the spring *S*, fixed at one end of the angle piece *C*, supports at its other extremity two fine wires, **W W′**, of the same size and material, these being stretched from the top to the bottom of the instrument. Only one of these (**W**) carries the current, the other being insulated. The needle **N** is unaffected by ordinary variations of temperature, as both wires expand or contract equally. But the moment **W** is heated by the current, it expands more than **W′**, and consequently develops a certain amount of sag, as the spring S is still held down by the wire **W**′. A hair-spring *ss*, fixed to the axle of the instrument, tends to turn the needle round over the scale, but is prevented from so doing by the bar B fixed to the wire **W**. Directly **W** is heated, however, the sag is taken up by B and *ss*, and its amount indicated by the movement of **N**.

The path of the current is as follows: From **T** + to C along S, down **W** to C', and thence to **T** –. The instrument shown reads up to 2·5 volts, which is just sufficient for the testing of a single secondary cell.

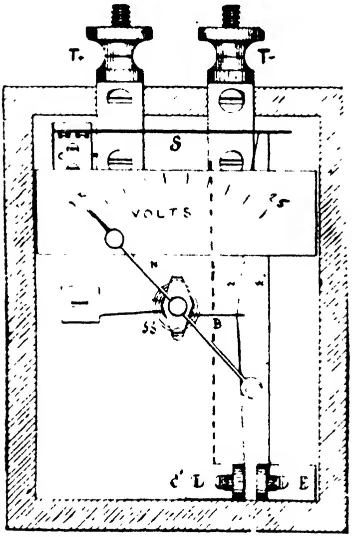


FIG. 321.—HOLDEN CELL TESTER.

Fig. 322 depicts the working parts of an ammeter of this description. **B** is a semicircular metal plate on which the parts are mounted. **C** is a brass clamp and **P** a pillar, and between these is stretched the platinum-silver current-carrying wire **W**. Both **C** and **P** are in direct metallic contact with **B**, and act not only as supports for the wire, but also as conductors of the current from the measuring-wire to the metal plate. The plate **B** is made of an alloy having the same temperature-coefficient of expansion as the wire **W**, so that the tension of the wire is unaffected by the expansion or contraction of the plate. In order that the expansion may be quite free, the plate **B** is attached to the ambroin base-plate **A** at one point only, viz., at its centre.

A second wire **W**′, of phosphor bronze, has one end attached to the insulated pillar **L**, and the other end to the wire W, a short-distance away from the middle point of the latter. A silk fibre F is attached to W′ near its centre ; and this, after passing round a pivoted pulley, is fixed to the end of a flat steel spring S. The pointer *p* is mounted on the same spindle as the pulley, so that any rotation of the latter is indicated by *p*. When the wire W sags under the heating effect of the current, the slackening of W′ is taken up by the spring S, the pulley and the pointer being consequently rotated. On the same

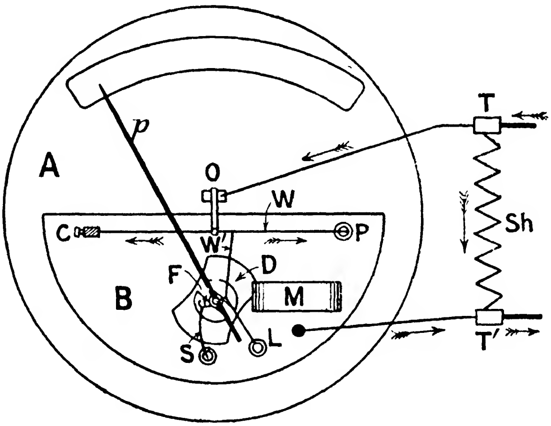


FIG. 322.—DIAGRAM OF HOT-WIRE AMMETER.

spindle is mounted an aluminium disc D, which moves in the magnetic field of a small horseshoe permanent magnet M ; and the eddy-currents induced in the disc damp its movement and render the instrument dead-beat.

O is an insulated piece of copper mounted on the base A, and connected to the middle of W by a zigzag conductor of silver foil. T and T′ are the terminals of the instrument, and between these is connected a constantin shunt Sh which carries the greater portion of the current to be measured.

The passage of the current along the measuring wire heats it so that it expands and sags, the wire W′ sagging to a proportionately greater extent. This sag is taken up by the spring S with the result that the pointer moves over the scale and indicates the value of the current passing.

If the instrument were a voltmeter, instead of Sh there would be an external resistance connected in series between O and T. Details of construction vary from time to time, but the foregoing sufficiently explains the principle upon which hot wire instruments act. A voltmeter reading up to 125 volts takes about 0·17 amps. at 100 volts.

Another form of thermal instrument consists of a permanent-magnet moving-coil ammeter across the terminals of which is connected a thermo-couple, consisting of two wires of dissimilar metals. The junction of these wires develops an e.m.f. if heated. The current to be measured is passed through a resistance which gets hot, and the heat from this warms up the thermo junction, in turn producing an e.m.f. which causes a current to flow in the moving-coil instrument. This type of instrument is convenient for many small alternating current measurements, particularly where the frequency varies.

253. HOT-WIRE RECORDERS. In certain cases, it is necessary or useful to have a continuous record of the current or pressure in a circuit during an extended period, say, a day or a week ; such record showing every variation and the time of its occurrence. Instruments for this purpose are called *recording voltmeters* and *ammeters*, and an example working on the hot-wire principle is shown in Fig. 323.

The current (which is proportional to the volts) passes through stretched wires at the top of the apparatus, and heats them to a greater or less extent, the sag thus brought about allowing the motion of an arm or pointer which terminates in a pen or pencil. A chart, divided by horizontal and vertical lines into voltage and time divisions, is mounted on a drum D containing clockwork, which rotates it continuously at the rate of one revolution every

24 hours, or at some other predetermined rate—$\frac{1}{4}$ in. or 1 in. per hour is found convenient in practice. The pen or pencil at the end of the arm bears against the paper, and thus a continuous line is drawn across the chart.

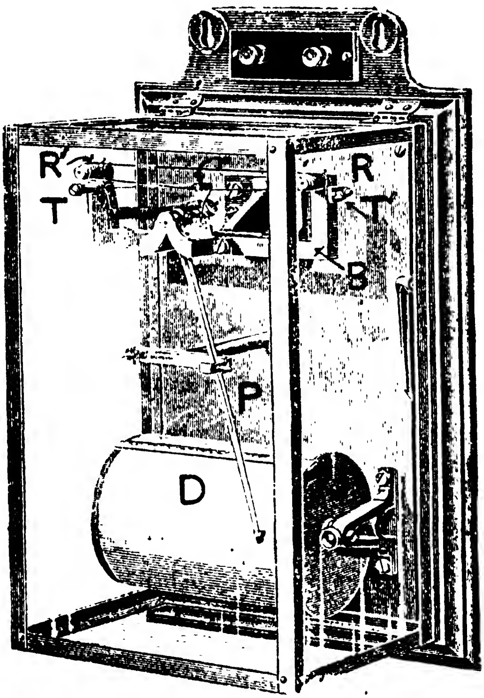


Fig. 323.—Recording Voltmeter.
(*Pitkin.*)

B is a brass bracket on which are pivoted two insulating rollers R and R′. Fine wire of special alloy is wound several times round R and R′, its ends being connected with the terminals T and T′. A smaller roller *r* of insulating material rests on the lower turns of wire, and when the latter sag owing to the heat developed by the current, *r*, which is linked to a small lever on the axle of the pointer or pencil, allows the latter to move by its own weight across the recording sheet. The current, the sag, and the deflection of the pencil are thus all three proportional to the pressure at the terminals. There is also an arrangement for compensating for changes of temperature other than those brought about by the current.

Hot-wire recording ammeters are very much the same in principle, except that the current, instead of going round the various turns of wire in series, as in the voltmeter, divides between them in parallel.

254. RECORDERS for current and pressure are made by different firms embodying the principles of the moving-coil, soft-iron and dynamometric instruments already described. Many ingenious devices have been invented in connection with the pens, inking, and charts, with a view to reduce friction between the marking portion and the paper, while long rolls of paper (instead of one merely covering the surface of the clock-driven drum) make it unnecessary to attend to a recorder daily. These instruments are of considerable service when consumers complain of defective or excessive pressure, as a continuous record can be taken which will show all fluctuations. They are also a means of detecting improper use of supply, by consumers taking abnormal currents (when starting motors, etc.), and for ascertaining the loads, and the times the maxima occur, on sub-stations and other outlying parts of a supply system.

255. ELECTROSTATIC INSTRUMENTS are based upon the forces of attraction between quantities of electricity of unlike sign, and repulsion between quantities of like sign.

The plates in a condenser are attracted by the + charge on one plate and the – charge on the other. In a condenser the plates are fixed, and separated by the insulating layer of dielectric between them.

An electrostatic instrument is a special form of condenser, in which one plate is fixed and the other is free to move, but the movement is restrained or controlled by a spring, wire under torsion, or gravity.

Such an instrument operates on the principle of an air condenser, one of the sets of plates being mounted on an axis so pivoted that its rotation increases or decreases the capacity of the instrument. When the fixed and movable plates are at different potentials, the electrostatic stress causes the movable plates to move in such a direction as to increase the capacity of the instrument, and the pressure applied is indicated on the scale.

Some of the very earliest measuring instruments were of this type. The simplest form is the electroscope, which became an electrometer when Lord Kelvin arranged the gold leaf behind a scale, so that the deflection or movement could be read on it.

Instruments of the electrometer type have an open circuit between their terminals. That is to say, they have an infinitely high resistance internally when in proper condition for use. They have the following advantages: (*a*) The current taken to operate them is but momentary on a direct current circuit, and infinitesimally small on an alternating current circuit; so that they neither consume energy nor introduce errors by altering the condition of the circuit to which they are connected.

Instruments of this class are peculiarly adapted for measuring high alternating pressures, as there is no complete circuit through them.

(*b*) They are absolutely unaffected by external magnetic fields, and (*c*) are insensible to changes of temperature. (*d*) Like dynamometer and hot-wire instruments, they are equally accurate on direct or alternating-current circuits of any frequency or wave-form. Their disadvantages are that (*e*) their range is somewhat limited, so that their scales are usually short; and (*f*) they are not sufficiently sensitive (except in expensive designs) to enable them to be used for the measurement of low voltages. (*g*) Owing to their construction and the limited demand for them, they are rather expensive.

Instruments of the electrostatic type are only available for the measurement of e.m.f.'s or p.d.'s, that is to say, as voltmeters. Pointer instruments are not sensitive enough to be sufficiently affected by a few millivolts across the ends of any practicable shunt, and cannot, therefore, be calibrated as ammeters. Only a very delicate—and therefore costly—instrument of the reflecting type could be worked by the small p.d. at the terminals of an ammeter shunt.

The **Quadrant Electrometer***—one of Lord Kelvin's instruments, far in advance of its time—is used for testing losses in the dielectric of cables. This and other instruments of the same kind are well worth study by the ambitious student, in view of the developments taking place in electricity supply, and the effects these will have upon the tests required to be made in future years.

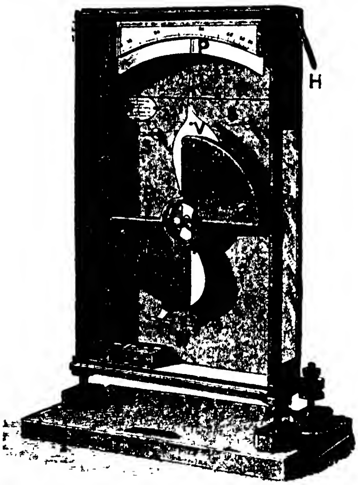


FIG. 324.—KELVIN VERTICAL SCALE ELECTROSTATIC VOLTMETER.

256. KELVIN ELECTROSTATIC VOLTMETER. Referring to the illustration of the vertical scale voltmeter, which is the simplest example of the class, in Fig. 324 V is a light aluminium vane which is supported in a vertical plane midway between the two interconnected fixed brass plates B B, forming an air-condenser, whose capacity will vary as the vane alters its position between the two fixed plates. The vane carries at its upper end an aluminium pointer P; while at its lower end (at W) are two pairs of nuts on screwed wires, one pair on a vertical

* See A. Gray's *Absolute Measurements in Electricity and Magnetism* (Macmillan, 42s.).

wire, and the other on a horizontal wire. The former allows the centre of gravity of the moving system to be adjusted, while the latter enables a zero adjustment to be made. Two or three small weights are provided for hanging on the bottom of V, and by means of these the range of the instrument may be altered. The fixed plates are connected to an insulated terminal, and the movable vane to an uninsulated terminal, both fixed at the back of the case. The vane and metallic case are electrically one so that they are at the same potential. This prevents any external charge having any effect on the indications. In order to save time by checking the oscillations of the vane, as the instrument is quite undamped, a fine horizontal insulated rod R, actuated by the handle H, may be brought forward so that the pointer rubs against it. The stops S S limit the range of movement of V, and prevent damage to the pointer.

When the instrument is joined up to any two points in a high pressure circuit, the p.d. between which it is desired to measure, the difference of potential causes the fixed and movable plates mutually to attract each other; and in consequence of this, the vane moves in between the fixed plates. The amount of this movement, and therefore the pressure to be measured, is indicated by the pointer on the scale, the exact value of the indications depending on the weights used as restoring or controlling force, and which have to be lifted against the pull of gravity when the vane deflects. Such instruments will measure from 300 or 400 up to 10,000 volts or 20,000 volts. Above these values the forces increase to an extent permitting of other forms which give wider air-gaps, and allow of the parts being farther removed from the observer.

The illustration gives a view of the form in which the voltmeter was made for many years. In the latest design the appearance has been altered somewhat, but the action is in no way modified. The older design shows the construction better, and hence has been selected for illustration.

257. THE KELVIN MULTICELLULAR VOLTMETER differs from the high-tension type in that it has ten moving vanes instead of one, and eleven fixed plates forming "cells" in and out of which the vanes move. Another point of difference is that the vanes are suspended on a

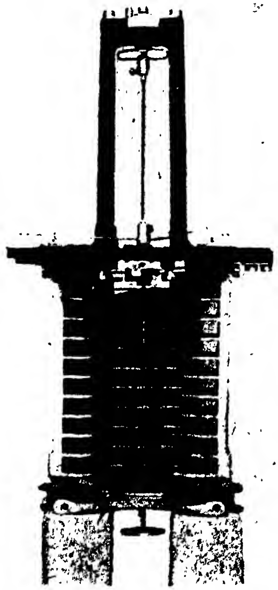


FIG. 325.—KELVIN MULTICELLULAR VOLTMETER.

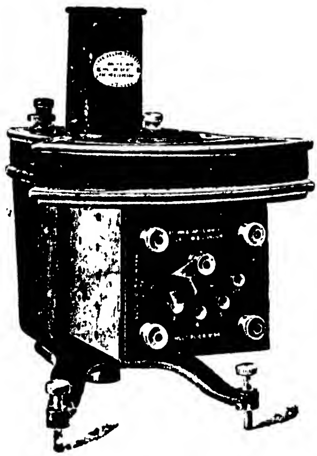


FIG. 326.—MULTICELLULAR VOLTMETER WITH MULTIPLIER.

vertical axis. Otherwise the principle of the two instruments is exactly similar, that now described being, of course, very much more sensitive than the single-vane pattern. In fact, the multicellular voltmeter will read as low as 30 volts, whereas the range of the single-vane instrument starts at about 250 volts. This greater sensitiveness is chiefly due to the greater number of vanes, and also to the smaller controlling force of the more delicate suspension The control in this case is the torsion or twist of the suspension as the vanes rotate.

The movable vanes, which are of aluminium, are fixed to a vertical spindle, which carries a light pointer at its upper end and a disc at its lower end, as will be seen in Fig. 325. The disc is immersed in an oil-bath (not shown), and this renders the movements of the vanes dead-beat. The spindle carrying the vanes, etc., is suspended from the top of the instrument by a fine platinum-iridium strip or ribbon, and means are provided at the top for adjusting the vanes and pointer to zero.

The scale is horizontal if the pointer is straight, as in Fig. 326, but indications can be given on a vertical scale by bending the pointer at right angles so that its index takes the form in Fig. 325. The external view is of a horizontal scale instrument. The box fixed in front is a resistance to be used as a potential-divider, and the connections have been given in Fig. 192.

258. STANDARD OF PRESSURE. The volt is defined as the electrical pressure which, when steadily applied to a conductor whose resistance is one ohm, will produce a current of one ampere. The standard of electrical pressure is an instrument, formerly in the custody of the Board of Trade and now at the National Physical Laboratory, constructed on the principle of Lord Kelvin's electrostatic voltmeter. As such an instrument cannot readily be made to measure one volt, this value is legally one hundredth part of the pressure which, when applied between the terminals forming part of the instrument marked " Board of Trade Volt Standard verified 1894 and 1909," causes that rotation of the suspended portion of the instrument which is exactly measured by the coincidence of the sighting wire with the image of the fiducial mark *A* before and after application of the pressure, and with that of the fiducial mark *B* during the application of the pressure, these images being produced by the suspended mirror and observed by means of the eye-piece.

In this particular instrument, instead of throwing a beam of light on to the mirror of the moving system, to which the vanes are attached, and reading the deflection by the reflected spot of light on a scale, the observer looks through a small fixed telescope at the mirror and sees reflected in it one or other of the two marks. The first, *A*, is a zero mark. When pressure is applied the movable system turns, and there is reflected in the mirror the image of the second mark, *B*, if the pressure between the vanes and cells is then exactly 100 volts. This is the favourite continental method of reading angular deflections, while in this country the beam of light and transparent scale are more generally used.

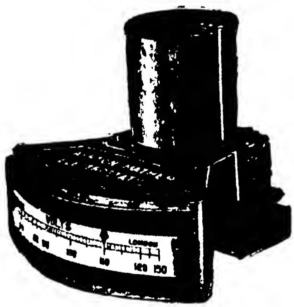


FIG. 327.

259. AYRTON-MATHER VOLTMETER. A pattern of this electrostatic instrument is shown in Fig. 327. This also depends for its action upon the mutual attraction of two bodies at different electrical potentials. The moving element (Fig. 329) consists of curved aluminium plates P P attached to—and concentric with—a pivoted spindle Sp, the plates being bent to form segments of a cylinder. A light pointer *p* is attached to the movement which is spring-controlled. The fixed element consists of two cylindrical brass segments S S fixed concentrically with the moving portion; S S having two lighter pieces S′ S′ fixed to them at one end and curving inside as shown.

The movement is pivoted on an axis coincident with the axes of the plates and of the fixed element; and when a potential difference is applied, the moving plates are attracted by the electrostatic forces into the spaces *s s* in the fixed portion.

Fig. 328 gives a view of the interior of the instrument removed from the case, and here will be noticed the helical controlling spring, and the circular and square ebonite slabs on which the parts are mounted. A cylindrical metallic shield fits over the working parts, and serves to screen the instrument from external electrostatic influences. The edge of the circular ebonite slab holds the shield in position, and a horizontal projection of the shield covers the needle and serves to screen it from the top of the case. The needle is far enough away from the bottom of the case to render screening on that side unnecessary. An opening at the top of the shield cylinder allows of easy access to the zero adjustment of the needle, and a slot at the bottom is made just large enough to allow of the free movement of the needle.

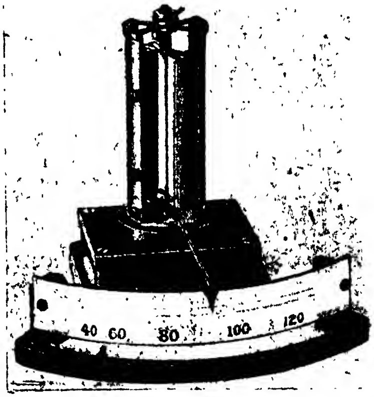


Fig. 328.—Internal Mechanism of Ayrton and Mather's Voltmeter.

One terminal of the instrument is connected to the shield, moving element, and insulated scale, which are all in metallic connection; and the other terminal to the fixed element. When a potential-difference is applied to the instrument, it will be obvious that the needle will be deflected to the right (from the zero position shown in Fig. 329) against the torsion of the controlling spring.

The case of the instrument is of sector shape, an outer cylindrical cover being fitted over the shield. The instrument is provided with two hooks at the back of the case by means of which it can be readily suspended on a special wall- or switchboard plate; or it can be used standing on a table or shelf. It is made either with a horizontal scale visible from above, for bench or portable use, or with a vertical scale (as in Fig. 328), for switchboard use.

The instrument is made in various capacities, that shown in Fig. 328 having a working range of 40-130 volts, such as would be useful on a 100 volt circuit.

260. ELECTROSTATIC INSTRUMENTS* may be roughly divided into four forms or classes—

(i) For very low pressures, *reflecting electrometers.* These have a moving vane or vanes with a reflecting mirror, being similar to magnetic or hot-wire reflecting galvanometers in this detail. The Kelvin Quadrant and Dolezalek electrometers are examples. In the latter the quadrants or fixed inductors are like a brass pill box cut into four and slightly separated, and the vane is made of silvered paper.

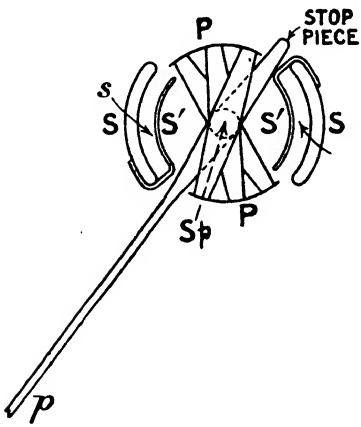


FIG. 329.—DIAGRAM OF AYRTON AND MATHER VOLTMETER.

(ii) For low pressures, *torsion electrometric voltmeters* (say, up to 30 volts). The vane is suspended by a fine wire, and readings are taken by restoring the vane to its original position by twisting the wire by means of a torsion-head. Compare with the Siemens electrodynamometer. Another method is to balance the pull on a plate against the force of a spring. Example, Kelvin's Absolute Electrometer.

(iii) For medium pressures, *deflectional voltmeters,* such as the Kelvin and Ayrton-Mather already described.

(iv) For very high pressures, instruments of large size, comprising a beam with an inductor, shaped like an umbrella hung at one end, with an oppositely-charged fixed inductor below. These are used in cable factories,

* See Chapters I and V, *Electrical Instruments,* by Murdoch and Oschwald (Pitman, 12s. 6d.).

for example, for stressing and breakdown tests on cables, and for the half-hour application of double working pressure tests to cables after laying and before being brought into use.

261. INDUCTION-TYPE INSTRUMENTS are gradually superseding other types for switchboards and control panels, but they are only available for use on alternating-current circuits. Their advantages are: (*a*) The absence of any moving iron; (*b*) the simplicity of the moving element, which is not electrically connected to the circuit; (*c*) they have long open scales; (*d*) they are dead-beat; (*e*) they are not easily affected by stray magnetic fields, owing to the intense concentration of the instrument's own field upon the moving element. On the other hand (*f*) they are affected by changes of frequency, and must therefore be calibrated at the frequency of the circuit on which they are used. For certain alternating-current instruments, the induction principle is the only one which can be employed.

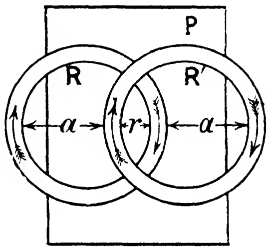


Fig. 330.

Such an instrument acts upon the same principle as the single-phase *shaded-pole motor*. In Fig. 330, **P** is one pole of a magnet excited by an alternating current, and **R R′** are two conducting rings which are free to move past each other. If either ring be by itself in front of the pole, the alternating magnetic field will induce an alternating current in the ring.

With the two rings overlapping each other, **R** would move to the right, and **R′** to the left until they were concentric, when no further lateral movement would take place. Suppose at any given instant the currents in the two rings were as shown by the arrows, then there would be repulsion at *r* and attraction at *a a*, and the rings would be drawn together. The induced currents are alternating, but they would be always in the same *relative* directions at any instant.

In Fig. 331, **P** is the same pole, **R** one of the rings (which this time is fixed to the face of the pole), and **D** a portion of a metal disc so pivoted that it can rotate just in front of **P** and **R** without touching them. If **R** were absent, the alternating field of **P** would induce currents in **D**, but there would be no rotation of the latter. When **R** is in place, **D** will experience a force rotating it in the direction shown by the top arrow.

The field over that portion of the pole which is covered or " shaded " by the ring **R** is less strong than that outside

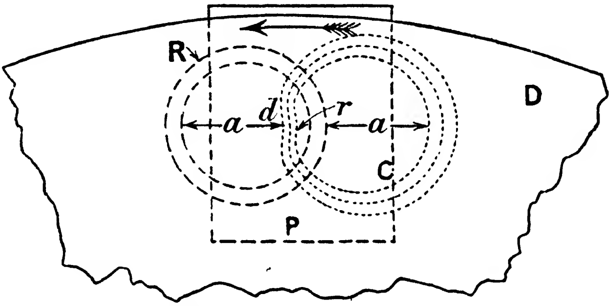


FIG. 331.—PRINCIPLE OF SHADED-POLE MOTOR.

the ring, as the shaded portion is partly neutralized by the opposing field due to the induced alternating current in the ring ; the ring's field being continually in opposition to that of the magnet pole. Although currents are induced in every portion of the disc which is in front of the pole, they are strongest in that part to the right of the ring.

These currents are represented by the curved dotted lines **C**, and they may be assumed to overlap **R**. Hence, to all intents and purposes, they are equivalent to the currents in **R′**, and there will be repulsion at *r* and attraction at *a a*, between the currents in the disc and those in the fixed ring ; and the disc will move in a direction of the curved arrow. As other portions of the disc come successively in front of the pole, fresh currents will be induced therein ; and the disc will be rotated continually as long as the pole **P** is excited.

262. SHADED-POLE INSTRUMENTS. Fig. 332 illustrates a voltmeter of this type. In voltmeters the actuating coil is of fine wire, a non-inductive resistance being connected in series with it. In ammeters the coil is of comparatively thick wire, and in both cases it is shunted by a compensating resistance. A voltmeter would be connected to the circuit either directly or through a shunt transformer, according to the circuit pressure ; while an ammeter is self-contained for currents up to 10 amps. provided the circuit pressure does not exceed 650 volts. Beyond that it is usual to employ current transformers with 5 amp. secondaries in combination with ammeters having 5 ampere-windings, but calibrated to read the main line current on the scale.

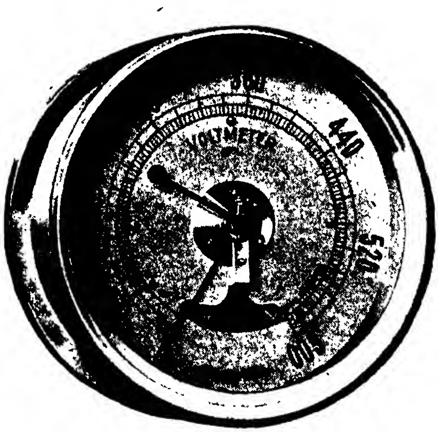


FIG. 332.—INDUCTION SHADED-POLE, LONG-SCALE VOLTMETER, WITH INDEX POINTER.
(*Metropolitan-Vickers.*)

The essential parts consist (Figs. 333 and 334) of a fixed electro-magnet with a ⊏ shaped core **K**, this being generally wound with a single coil **C** on the lower pole ; and a pivoted aluminium disc-shaped rotor **D**, whose outer portion passes through the small air-gap of the core **K**, the pointer **P** being fixed to the spindle of the disc. The short-circuited *shading coil* **S** is formed by fixing a single turn of copper strip around one-half of the laminations forming the upper pole of the magnet, and joining the ends together. A similar coil is placed on the lower pole, opposite the top one. The copper strip let into the face of the core is equivalent to the ring **R** in Fig. 331, and the disc **D** of the instrument will experience a force tending to turn it in a clockwise direction. The movement of the disc is retarded by the spring **Sp**, so that it will only move round to a point at

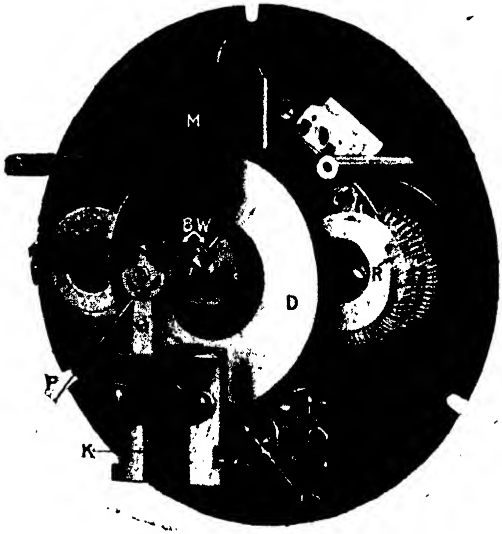


FIG 333 —SHADED-POLE INSTRUMENT (COVER AND DIAL REMOVED).
(*Metropolitan-Vickers.*)

which the force acting on it is balanced by the controlling force of the spring. Thus the distance it will turn depends on the strength of the current in the coil **C**, that is to say, on the p.d. at the terminals of the instrument.

The disc has a slot *s* cut in it, and its outline is of diminishing radius. Starting from the zero position shown in Fig. 333, the area passing between the poles gradually decreases. This renders the deflections of the disc proportional to the current, and so permits of a uniform scale. If the disc were uniform, the deflections would be proportional to the square of the current. The disc spindle is pivoted in jewelled bearings, and carries balance-weights **B W**, the controlling force being supplied by a fine spiral spring **Sp**. **B W** makes up for the irregular shape and weight of the disc, and if there were no controlling spring to bring the pointer to the zero position, the disc would remain steady in any position. *r s* is a rubber stop to limit the movement of the disc, and so prevent the pointer passing too far beyond the end of the scale. The movement of the disc is steadied by the

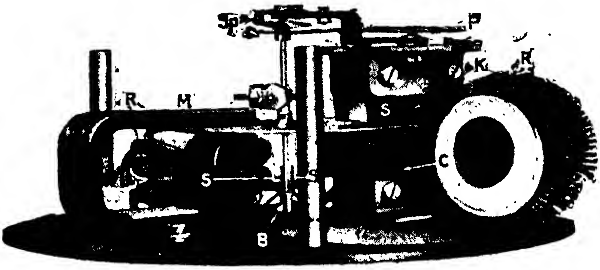


FIG. 334.—SHADED-POLE INSTRUMENT (ANOTHER VIEW OF INTERIOR).
(*Metropolitan-Vickers.*)

"damping" action of the permanent magnet **M**, so that indications are rendered dead-beat.

The back bearing in which the spindle carrying the disc, etc., is pivoted, is carried in the brass shank **B**, which forms a continuation of a screw passing through from the back of the case. Thus **B** can be withdrawn by turning this screw, the spindle being then held fast by the spring **S S**, as shown in Fig. 334. When **B** is screwed in, it forces the springs apart, and sets the spindle free in its bearing. This arrangement is very useful in protecting the spindle from harm while the instrument is being carried about.

R R are two non-inductive compensating resistances, which are connected in shunt across the magnet coil **C**. In Fig. 334 one of these resistance coils is moved out of place to enable the coil **C** to be seen. Were it not for **RR**, slight changes of frequency would affect the indications. If the frequency rises, the inductance of **C** will increase, and more current will be shunted through **RR**; and vice versa.

This resistance also compensates for changes of temperature. While an increase of temperature has little effect on **C**, because its resistance is low as compared with its inductance, it causes an increase in the resistance of the moving disc. Such increase would reduce the turning moment of the disc, because the eddy currents induced therein would be reduced in strength; with a decrease, the opposite would be the case. The meter would therefore read slightly too low with an increase, or too high with a decrease of temperature, were it not for **RR**, which is purposely wound with wire of a material having a higher temperature-coefficient than the material of the coil **C**. With an increase of temperature—for example—the proportion of current flowing through **C** is increased, and the turning moment of the disc is maintained at its proper value in spite of the increase in its resistance.

The principle of alternating-current instruments will be better understood after studying alternating-current phenomena, in Chapter XIII.

263. THE WATTMETER. The power absorbed in any given part of a **direct-current circuit** may be ascertained by connecting a voltmeter to the extremities of the part under consideration, and at the same time inserting an ammeter in the circuit. Then the product volts × amperes = watts. The same process may also be applied to non-inductive alternating-current circuits.

Wattmeters are instruments which combine the principles of a voltmeter and an ammeter, and which directly indicate the power used in a circuit. In the *dynamometer-type* wattmeter there are two coils or sets of coils, one of which is fixed and the other movable. The fixed coil is connected in the current circuit, and the moving coil in the pressure circuit, as a rule. Another type of wattmeter—known as the *induction type*—can only be used on alternating-current circuits.

With the increasing use of alternating currents the importance of the wattmeter, as a measuring instrument in the commercial selling of electrical energy, is becoming greater every year. So long as direct currents were the common means of supplying the public, ammeters and

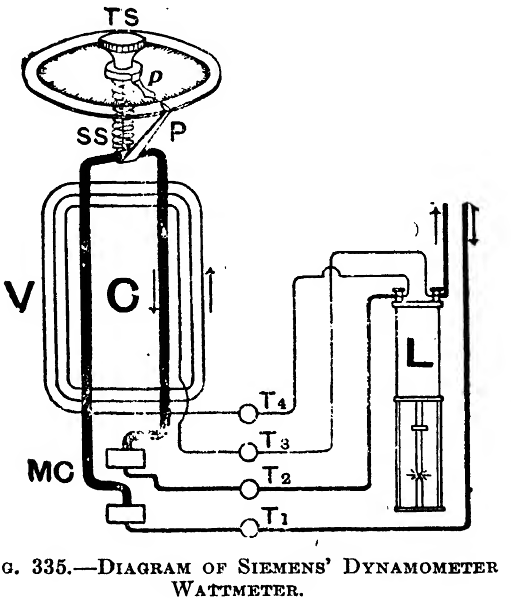


Fig. 335.—Diagram of Siemens' Dynamometer Wattmeter.

voltmeters were sufficient for most of the work which had to be done to ascertain loading on motors, maximum demands, and so on. Now that *apparent power* is one thing and *real power* another, engineers on alternating systems need not only ammeters and voltmeters but wattmeters as well. The ratio between apparent and real power can then be ascertained; the apparent power giving the heating effect on transformers and alternators, and the real power the driving power required. The capital cost incurred in laying down a system is roughly proportional to the apparent power ; its revenue producing capacity to the real power, unless some charge be made for kilo-volt-ampere hours as well as kilowatt-hours.*

264. DYNAMOMETER WATTMETERS. The Siemens wattmeter was the pioneer of this class of apparatus, and the principle of the instrument is indicated by the diagram in Fig. 335. Its construction is similar to that of the electro-dynamometer, the main difference being that the fixed and moving coils are not connected together inside the instrument. It may be used to measure either direct or alternating-current power, if an external or swamping resistance be joined in series with the pressure coil.

C is a coil of thick wire, which is suspended by a thread and which is free to turn against the torsion of a helical spring SS, which also acts partly as a suspension. In this diagram the current coil is the movable one, because it has fewer turns and is of heavier gauge. C is connected, through mercury cups MC, with the terminals T_1 and T_2. Inside C is a fixed coil V of fine wire, the ends of which are in connection with the terminals T_3 and T_4. The coil C has a pointer P attached to it, which indicates the amount of its movement upon the scale above it. The normal position of the coil C is as shown in the figure, i.e. with its plane at right angles with the plane of the fixed coil.

If both coils carry current, the coil C will tend to turn so that its plane shall lie parallel with the plane of the coil V ; this action being due to the attraction and repulsion set up between the sides of the coils. The magnetic field of the moving coil tends to turn (and to take the coil with it) so that it lies parallel with, and in the same direction as, that of the fixed coil.

To use the instrument, T_1 and T_2 are joined up so that the main current passes through the coil C as if it formed an ammeter coil. The terminals T_3 and T_4 are connected with the two points of the circuit between which it is

* See H. M. Sayer's "Electricity Supply Costs and Charges" (*Electrical Review*, 3s.).

desired to measure the power ; for instance, to the terminals of an arc lamp **L**. The coil **V** thus acts as a voltmeter coil.

The turning force exerted by the coils is proportional to the product of the strengths of the currents in them ; and as the current in **V** is proportional to the volts, the turning force is consequently proportional to the product.

A reading is taken by finding how much the spring **SS** has to be turned in order to bring the coil **C** back to its

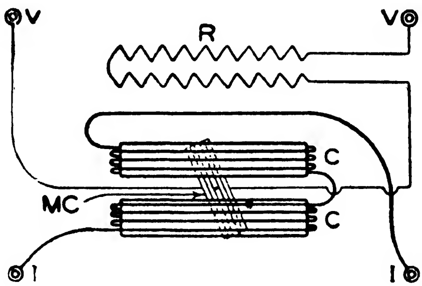


FIG. 336.—WATTMETER COILS.

zero position. The instrument is not a direct-reading one , it must be calibrated, that is to say, the angle of torsion corresponding to a known power must be ascertained. Unlike the electro-dynamometer, however, the deflections are *directly proportional* to the values producing them.

In other and later patterns of this apparatus the pressure coil is made the moving one, and the mercury cups are dispensed with, the current being led to and from the moving coil through fine flexible wires. Further, a non-inductive fixed high resistance is generally connected in series with the moving coil. The current coil is then fixed and there is no difficulty in carrying the line current through it, as its circuit is a permanent one and can be readily insulated for the line pressure to earth.

The internal connections are then as shown in the diagram, Fig. 336, where **C C** are two fixed thick-wire current coils connected in series to the current terminals I, I; and MC is the movable fine-wire coil, in series with the fixed high non-inductive external or swamping resistance R, and connected to the voltage terminals V, V. The fixed and moving coils thus act as current and pressure coils respectively, and measure simultaneously the current and p.d., and hence the true watts in the circuit.

265. ALTERNATING CURRENT WATTMETERS. In a dynamometer wattmeter, the turning force exerted by the coils at any instant is proportional to the product of the values of the currents in them at that instant, one of these currents being that due to the pressure.

The turning force at any moment is, therefore, proportional to the product of the instantaneous values of the current and the pressure, and so to the instantaneous watts. Consequently, the effective turning force is proportional to the watts.

When the pressure and current change together, i.e. are in phase, the product of the instantaneous values is always positive, hence the moving system of the wattmeter is always deflected in the same direction. Should the current change its direction when the pressure is at a maximum, i.e. be 90° out of phase, the turning force would be acting equally in alternate directions, and since the changes in direction follow one another in quick succession, the wattmeter pointer would simply remain stationary and indicate no power.

For anything intermediate between these two conditions, the turning force would be greater in one direction than the other, consequently, the moving system would be deflected by an amount equal to the real power. Thus it is that a wattmeter indicates the true watts in the circuit, or $E \times C \times$ power-factor; while the product of voltmeter-reading by ammeter-reading gives the volt-amperes, or apparent power.

266. WATTMETER COMPENSATION. When a wattmeter of the dynamometer type is used to measure the power absorbed in any given circuit, the instrument can be joined-up in either of two ways, like the ammeter and voltmeter in Figs. 195 and 196.

(*a*) The pressure or shunt coil **Sh** may be connected right across the current (or series) coil **Se** and the power-absorbing circuit **L**, as shown in Fig. 337. In this case the p.d. measured by the shunt coil is the sum of the p.d. across **L** and the voltage-drop across the series coil **Se**. The reading on the instrument, therefore, includes the power absorbed in the series coil.

(*b*) The shunt coil may be joined-up as in Fig. 338, so that the pressure across it is simply the p.d. between the

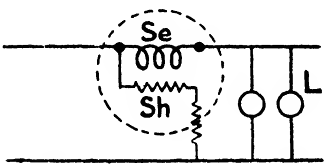


Fig. 337.

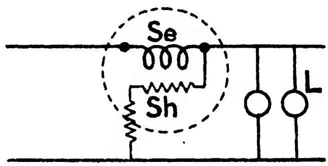


Fig. 338.

Connection of Wattmeter in Circuit.

ends of the power-absorbing circuit **L**. With this method of connection, however, the current through the series coil is the sum of the current in **L** and that in the pressure coil **Sh**. Thus the reading on the instrument includes the power absorbed in the shunt coil.

The method of connection, given in Fig. 337, is the one usually employed ; and in ordinary work, where the power measured is fairly large, it is not necessary to make any correction for the watts absorbed by the series coil. When needful, however, the resistance of the series coil can be ascertained, and the C^2R loss in **Se** calculated, C representing the current passing through the instrument during the test.

When a wattmeter is connected up to the circuit in the manner shown in Fig. 338, compensation can be provided for the error due to the shunt current passing through **Se**. This consists of a compensating coil which is wound over—

and has the same number of turns as—the series coil, but is connected in series with the pressure coil. As it is wound in the opposite direction to the series coil, its magnetic field neutralizes that due to the shunt current passing through the series coil. The object of the compensating winding is to allow for the energy required to operate the instrument; its effect on the moving-coil being so adjusted that the watts indicated on the scale of the instrument are those representing the external power to be measured, and thus the instrument reads quite correctly.

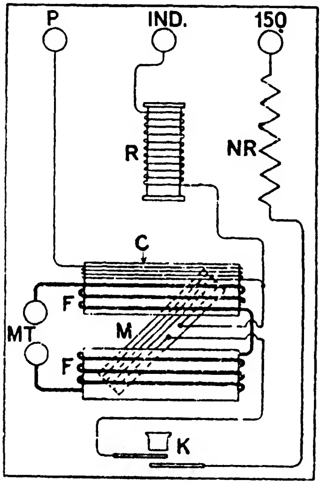


FIG. 339.—DYNAMOMETER WATTMETER.

The connections of a wattmeter with a compensating coil are given in Fig. 339. In addition to the resistance in the pressure circuit, the moving-coil has also in series with it either a compensating winding wound upon the same frame as the fixed coils, or else an additional resistance wound upon a small bobbin, and equal in value to the resistance of the compensating winding. Whether the compensating coil or its equivalent resistance be in circuit depends upon which terminals are used.

M is the moving-coil, **F F** the fixed coils, **C** the compensating coil, **NR** the series non-inductive resistance, **R** the alternative resistance which takes the place of the compensating coil when the terminal *IND.* is used, and **K** a key in the pressure circuit. 150 and **P** are the terminals which are used for tests up to 150 volts, and **MT** the main or current terminals.

267. WATTMETER CONNECTIONS. Instruments of the ordinary or average range are connected directly in circuit, as seen in Fig. 340, provided *E* and *C* do not exceed about 300 volts and 20 amps. respectively. The current range may be increased up to about 100 amps. by providing a thicker winding on the fixed coils or by split coils, and the pressure range by inserting external resistances, or " multipliers " in series with the pressure coil, as in Fig. 341.

As an example, in a wattmeter reading up to half a kilowatt for 5 amps. in the current coil, and 100 volts across the pressure coil circuit, the latter was arranged with a multiplier for 200 volts, and the resistances were : Res. of 100 volt pressure circuit 1,329ω. This was made up of coil = 82ω with external res. of 1,247ω. The external multiplier had a resistance of 1,329ω. The resistance of the current coil of this wattmeter is 0·081ω.

Data of Four Typical Wattmeters of Different Makes and Ranges.

Current Coil.		Pressure Coil.	
Max. Current.	Resistance.	Resistance.	Voltage.
0·5 amps.	7·81 ohms.	2,720 ohms.	100
5·0 ,,	0·145 ,,	3,310 ,,	100
15·0 ,,	0·02 ,,	3,300 ,,	100
100·0 ,,	0·00115 ,,	6,400 ,,	100

Figs. 340, 341, and 342 show the connections of a wattmeter to the external circuit in three different cases. Fig. 340 illustrates the method of connection for all purposes when the field and pressure circuits are connected to the same external circuit, and when the pressure is not more than 150 volts. Fig. 341 shows the connections under similar circuit conditions when the pressure is above 150 volts. In this case a multiplier is inserted in series with the pressure circuit of the instrument.

In certain cases (for instance, when the external main and pressure circuits are independent, that is to say, when they are not electrically connected together on one pole), the presence of a compensating winding in the field circuit would cause an error. In such a case the third pressure terminal *IND.* is used, this being connected to the coils through the equivalent resistance **R**, Fig. 339. Thus when the pressure is applied between the terminals marked *IND.* and 150, though the compensating winding is cut out, the resistance of the pressure circuit remains the same.

Fig. 342 shows the method of connection for all purposes when the field and pressure circuits are connected to entirely independent circuits, as in calibrating or checking the instrument; or as in some measurements with what are

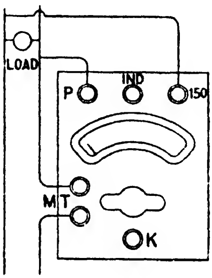


FIG. 340.

ORDINARY DIRECT CONNECTION.

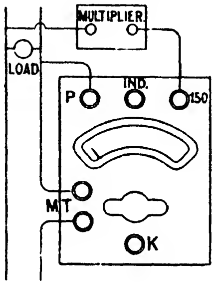


FIG. 341.

CONNECTIONS WITH MULTIPLIER.

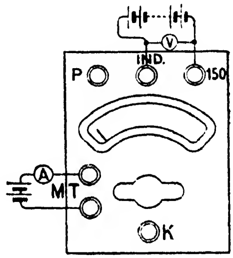


FIG. 342.

CONNECTIONS FOR CALIBRATION.

termed "phantom loads," when the main current is derived from the secondary winding of one transformer, which may have only a low voltage; and the pressure from an independent secondary winding of the same or of a second transformer, which may give only a small current.

When—as in a similar case—the instrument is being calibrated by connection to two independent circuits (usually battery circuits containing respectively a standard ammeter **A** and a few large cells, and a standard voltmeter **V** with a large number of small cells), the power indicated by the standards does not include that expended in the wattmeter. The necessity then arises for eliminating the neutralizing effect of the compensating winding by using the terminal marked *IND.*

The contact key K is provided on precision patterns, so that the pressure circuit need only be closed during the taking of the reading.

Wattmeters are principally of use on alternating-current circuits. It will be understood that the current coil is treated like an ammeter and the pressure coil like a voltmeter, hence if the current exceeds 20 amps., or whatever the carrying capacity of the current-coil may be, a current or series transformer is used, as shown in Figs. 343 and 345.

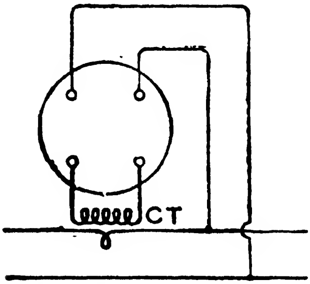


FIG. 343.—CONNECTION OF WATTMETER THROUGH CURRENT TRANSFORMER.

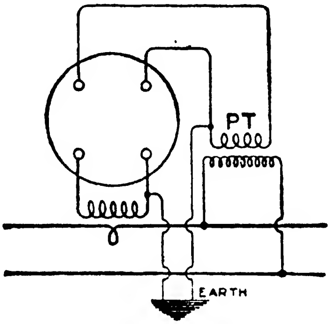


FIG. 344.—CONNECTION OF WATTMETER THROUGH CURRENT AND POTENTIAL TRANSFORMERS.

On high-tension a.c. circuits, besides the series transformer in the current circuit, a potential or shunt transformer is inserted in the pressure circuit, as in Figs. 344 and 346.

When instruments are used with transformers in this way, the indications of the pointer must be multiplied by the "transformer ratios" to get the true power, just as a shunted galvanometer must be multiplied by the power of the shunt to get the equivalent unshunted deflection.

It should be noted that if several instruments are used together, the current coils of wattmeters and energy meters and ammeters are connected in series with the consumption circuit or load; and the pressure coils of wattmeters and energy meters and voltmeters are connected in parallel across the consumption circuit or load.

The connection to earth, in Fig. 344, is a safety precaution in case of leakage, and does not affect the working of the instrument. Care must be taken that no other earth exists

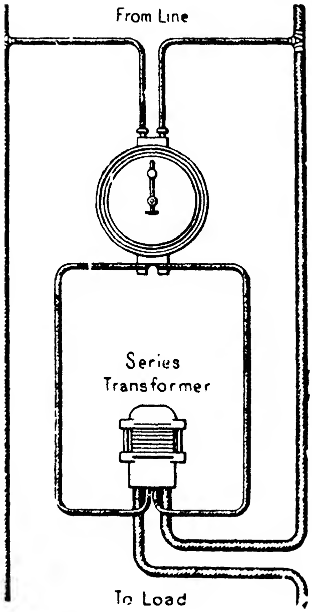


Fig. 345.—Connection of Wattmeter to Low-pressure Circuit.

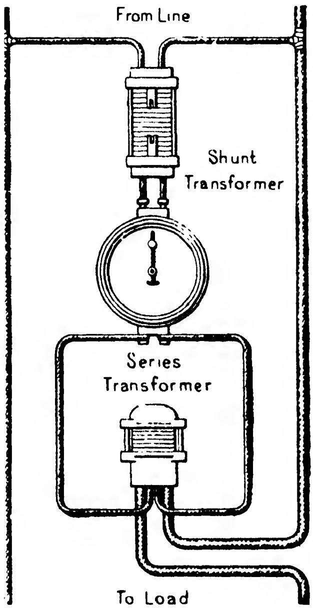


Fig. 346.—Connection of Wattmeter to High-pressure Circuit.

anywhere else, and that the side of the circuit connected to earth is that normally nearest to zero potential. The diagram is correct for laboratory tests to ensure safety to the operator. Some such precaution should always be observed.

There is practically no limit to the range in kilowatts for which a comparatively low-reading instrument may be adjusted and calibrated. But, for refined measurement, an instrument intended for connection to transformers should be checked throughout its range with the particular external apparatus with which it will be used in service.

268. WESTON WATTMETERS. These are similar in construction to the Weston dynamometer voltmeter, the main differences being that there is no electrical connection within the instrument between the fixed and moving coils, and the fixed coils are of thick wire, and carry the main circuit current. The fine-wire moving coil, in series with a non-inductive resistance, is connected to the points in the circuit to which the apparatus, consuming the power to be measured, is joined.

The moving coil carries the pointer or index needle, and is mounted on an axis provided with pivots turning in jewelled bearings. Thus when the coil is traversed by a current, it can turn until it finds its position of equilibrium ; the force deflecting it depending upon the product of the current in it and that in the fixed coils. Thus it is that the indications of the instrument are proportional to the power in watts.

In order to damp the vibrations of the moving-coil, and make the instrument dead-beat, an aluminium vane with two pistons moving in a closely-fitting air-damper box is mounted below the coil, and on the same axis.

In the precision patterns, on the scale-plate beneath the needle, there is a curved slot in which a mirror is inserted. This mirror reflects the needle and prevents parallax error in reading. The instrument is normally made for a maximum pressure of 150 volts ; but only a small proportion of the pressure across the volt terminals is applied to the moving-coil itself, as the latter is connected in series with a non-inductive resistance made of an alloy having a negligible temperature coefficient.

The pressure terminals are to be seen at the left-hand side of the instrument in Fig. 347, with the key below them. The current terminals are at the top with the split-coil terminals at the right-hand corner. As the current-range changing-links are shown, the two sections of the coil are in parallel.

For **switchboard purposes** the constituent parts are mounted on a circular base, with terminals projecting through for back-connection. The interior of a modern

FIG. 347.—WESTON DYNAMOMETER WATTMETER (WITH TWO PRESSURE AND TWO CURRENT RANGES).

form, called Model 167, is seen in Fig. 348. **C** are the two current coils connected to inside terminals at *t t*. **MC** is the moving coil which is mounted, together with the pointer p_1, on the pivoted spindle *s*. The ends of the moving coil are connected to the spring connectors *b b′*;

w is a wire connecting spring *b* with one of the pressure terminals; and *w′* connects *b′* to the high resistance *R*, the other end of which is joined up to the other pressure terminal. The resistance consists of special wire wound on thin micanite sheets; this construction giving a high insulation combined with a large radiating surface. Aluminium damping vanes enclosed in air chambers **AC**

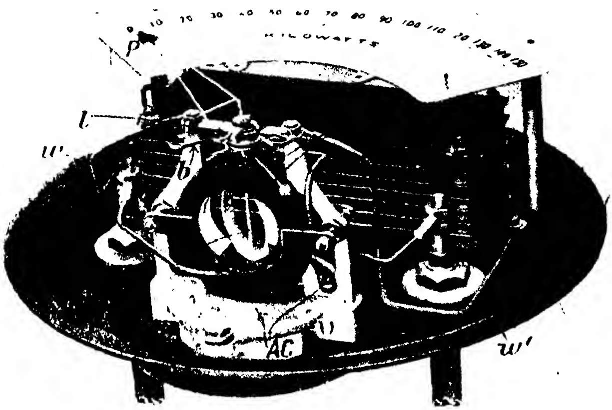


Fig. 348.—Interior of Weston Switchboard Wattmeter.

render the instrument dead-beat. The vanes fit the air chambers very closely, without touching, of course.

The two light spiral springs *b b′* are coiled in opposite directions. They act as the controlling force of the instrument, the deflection of the moving coil taking place against the force of these springs. The springs also lead the current of the pressure circuit into and out of the moving coil, their outer ends being joined to the lugs to which *b b′* are connected. One of these lugs or abutments *l* has a small range of adjustment to allow of zero-setting of the pointer.

On low-power factors a wattmeter tends to read high (i.e. the true power is less than the instrument indicates). This is caused by the inductance of the pressure coil, which causes the current through it to lag behind the pressure applied to its terminals. Hence, in such cases, special care

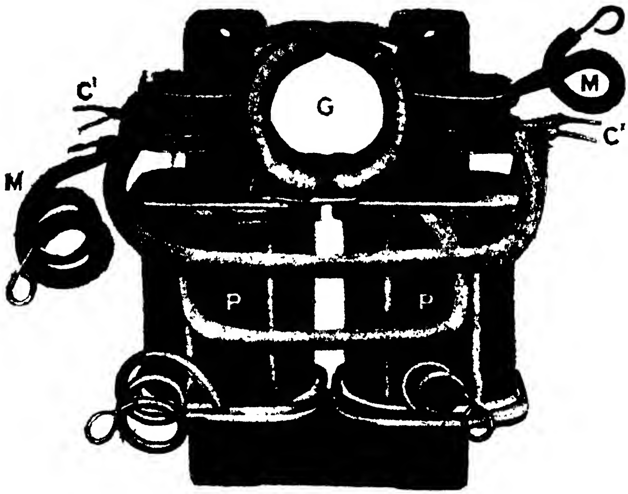


FIG. 349.—MAGNET OF SINGLE-PHASE WATTMETER.
(*Metropolitan-Vickers.*)

has to be given to the methods employed for ascertaining the true power.

269. INDUCTION WATTMETERS. An example of an instrument of this type, for the measurement of power in a single-phase alternating-current circuit, is illustrated in Figs. 349 and 350. There are two circuits in the instrument, through which the main and pressure currents are led.

The actuating portion of the instrument consists of a horseshoe laminated iron-core *C*, with curved poles, and a rotating aluminium cylinder or drum, carrying the pointer, is fitted in the gap *G*.

The interior of the instrument is shown in Fig. 350, and a view of the magnet and windings in Fig. 349.

P P are the pressure coils, which are joined-up in series with the full line pressure on them ; and **M M** are the main coils (one on each pole-piece), these being also connected in series.

C C are two coils embracing the pole faces, and curved round the sides and through the small air-gaps at top and bottom ; and their connections are shown in a half-finished state at **C′ C′**. The object of these coils is to compensate for inductive loads of various power-factors, and on non-inductive loads they would not be necessary.

The pressure circuit **P P** obviously has much greater inductance than the main-current circuit **M M** ; and the current in and magnetism due to **P P** consequently lag behind the current in and magnetism due to **M M**, so that a rotating field is set up in the air-gap **G**. This field acts on and twists the drum round against the force of the controlling spring, to an extent proportional to the product of the pressure and the current in the circuit, that is to say, to the power therein.

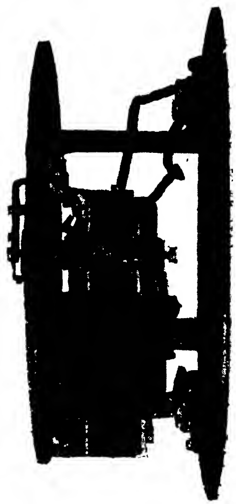


FIG. 350.—SINGLE-PHASE WATTMETER. (SIDE VIEW OF INTERIOR.) (*Metropolitan-Vickers.*)

A wattmeter indicating the peak load on a generating station is reproduced in Fig. 351. The dotted or phantom pointer gives the position of the index when the whole of the plant would be fully loaded up. The long scale will be noted, rendering it easy to read the power at any time and from a distance.

Other makes of wattmeters differ in details of construction ; but if the principles already given have been understood, it is unnecessary to illustrate these differences to explain the main features of a power-indicating instrument. Some firms make wattmeters with a moving scale and fixed pointer by utilizing an energy meter ; but instead of allowing the disc to revolve, it coils up a spring until the torque is balanced (see Chapter XVIII). An electrometer can be used as a wattmeter, and is so employed to measure dielectric loss and other quantities, difficult to ascertain by other means.*

FIG. 351.—SWITCHBOARD WATTMETER.

270. WIRING RULES. One of the marked differences between gas or water supply and electricity supply is that, in the latter case, there is no serious attempt at storage ; everything that happens in the works is reflected all over the system. Another difference is that if a pick or wedge be driven into a gas or water pipe, while leakage will result, that leakage is not sufficient to permit of the network of pipes emptying itself through the leak. If the same thing occurs on an electric main, the resulting short-circuit causes the whole, or the major portion, of the energy of the system

* See Chapter V, *Electrical Instruments*, by Murdoch and Oschwald (Pitman, 12s. 6d.).

to be concentrated momentarily at that point, until a fuse blows or some other protective device cuts off the supply.

A leakage on the premises of a consumer may set fire to the premises; it may also cause an interference with the supply in other parts of the system. Consequently, it is the practice to draw up rules for the guidance of consumers, and to ensure that work done by contractors is of a satisfactory character. The Electricity Supply Acts make four broad stipulations: (*a*) that supply shall not be taken in such a manner as to interfere with the supply to other consumers connected to the same system; (*b*) that the leakage current from a consumer's premises shall not exceed one ten-thousandth of the current taken thereon; (*c*) that wiring and fittings shall be in good order and condition; and (*d*) that the maximum power shall be specified and not exceeded.

To prevent perceptible flickering of lights in one premises by the turning on of current to motors, the pressure at which the latter are supplied is made as high as possible, often twice the lighting pressure, and the variation in current must be such, say, that not more than full-load current shall be taken at any time. The less the consumer is "regulated" the better, but there are certain well-defined requirements that should always be complied with.

The intent and meaning of most of the regulations met with should be understood from the laws of electric flow, and the deductions from them which have occupied the preceding pages of this book, and whose application takes up a considerable portion of Vol. II.

QUESTIONS

1. You are asked to determine the relative electrical value of samples of insulated copper wire. What tests would you make (and how would you make them) in order to determine whether the wire may be considered as being of satisfactory manufacture?

2. State the tests applied to electric cables during manufacture; describe briefly how the tests are made and the apparatus necessary for the purpose

3. How would you proceed to determine the copper resistance

and the insulation resistance of an insulated cable ? What is me by electrification in an insulated cable, when the cable is tested insulation ?

4. On the label attached to a coil of insulated cable you fin stated that the coil has been tested after 24 hours immersion water, and that the insulation resistance is 600 megohms per i at 60° F. Why has it been immersed, and why is the temperat mentioned ? What will be the insulation of a piece of this ca 110 yds. long ? *Ans.* 9,600Ω.

5. A specimen of insulated conductor, about 100 ft. long submitted to you to test. It is said to have an insulation resista of 2,000 megohms per mile after soaking in water for 24 hours, when tested at 600 volts at a temperature of 60° F. Describe exac how you would ascertain whether this was true, and mention all precautions you would adopt to avoid errors.

6. Explain the principle of Price's guard wire, and show hov may be employed to avoid error in measuring the insulation re tance of a short piece of cable by the loss of charge method.

7. What is meant by the "insulation resistance" and "dielec strength" of an insulating cloth ? How can you find these quanti experimentally ?

8. Explain what is meant by the term "insulation resistance a circuit to earth." If an electrostatic voltmeter is connec between the positive wire of a 200-volt electric lighting circuit a earth, what reading would you expect to get ? *Ans.* With perf insulation 100 volts ; usually about 50 or 60 volts.

9. A galvanometer in series with a megohm and a 20-volt batt shows 30 scale divisions when connected on one side to the circu whilst the free pole of the battery is earthed. The same galva meter and Ω, when connected to a standard cell of 1·019 vo shows a deflection of 10 scale divisions. What is the insulat resistance of the circuit ? *Ans.* 5·542Ω.

10. What tests would you carry out to satisfy yourself that t work done in a building was wired satisfactorily ?

11. Describe how you would measure the insulation resistan of the "wiring" of a building. Give a diagram of connections some form of portable testing set suitable for the purpose.

12 What is the construction of an ohmmeter ? Describe a direct-reading instrument with which you are acquainted, and sh by a diagram its connections.

13. What apparatus would you use, and how would you procee to test the insulation resistance of the wiring of a house befo connecting to supply mains ? Give details of your instrumen measurements and the values you would expect to get, stati the minimum for a 100 point installation. *Ans.* ½ megohm.

14. You are required to test and certify to the condition regards insulation of the distributing conductors laid undergrou in a town. How would you proceed to do this ?

15. Describe a method of testing an underground cable for (capacity, and (*b*) insulation

16. It is required to measure the insulation resistance of a lar continuous current armature in a supply station, where continuo

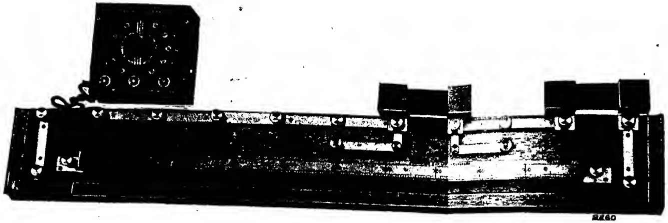


FIG. 220.—ROBERTSON TYPE OF SLIDE-WIRE BRIDGE.
(*Crompton*)

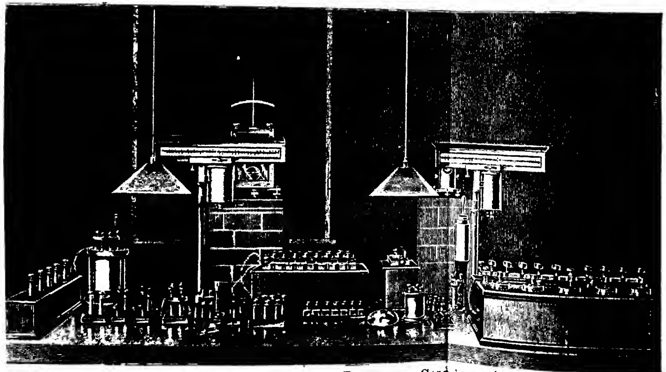


FIG. 242A.—FACTORY CABLE-TESTING ROOM, WITH REFLECTING GALVO'S, BRIDGE, SHUNTS, STANDARD MEGOHM, CONDENSER, AND KEYS.

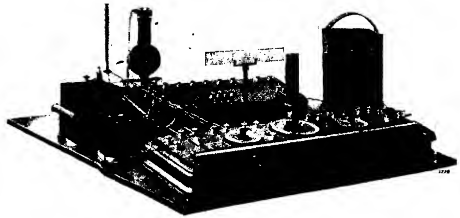


FIG. 230.—CROMPTON POTENTIOMETER, WITH REFLECTING GALVO., STANDARD CELL, CURRENT-RESISTANCE, VOLT-BOX, AND POTENTIOMETER BATTERY.

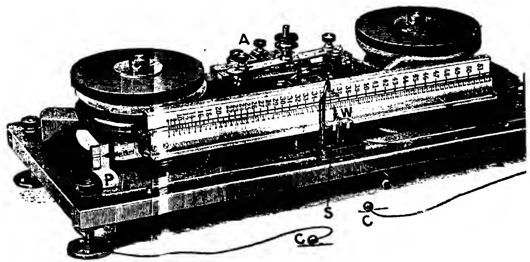


FIG. 317.—LORD KELVIN'S DEKA-AMPERE BALANCE.

(T.5104) *bet. pp.* 486 *and* 487.

current at 500 volts is generated. What apparatus would you ask for, what data would you require, and how would you proceed ?

17. How can the resistance of an earth be measured ? Show how the individual resistances of three earth-plates, not necessarily of the same size, can be ascertained.

18. If there are three pilot wires between two generating stations, how could you determine the resistance of each wire without the employment of a fourth wire or having to put the further ends to earth ?

19. Three circuits A, B, and C are successively looped together, and the resistance of each loop measured ; the resistance of A and B is found to be 260 ohms, of A and C 280 ohms, and of B and C 300 ohms ; determine the individual resistance of A, B, and C. *Ans.* A 120 ; B 140 ; C 160.

20. There are two wires, a and b, between stations A and B ; there is an earth at A which is known to be good, whilst another earth at B is assumed to be defective ; a and b are first looped at B, and a measurement of the resistance of the loop made at A ; a and b are then successively put to earth at B, and resistance measurements made at A. Show how the resistance of the earth at B could be found from these measurements.

$$Ans.\ x = \frac{(a + \mathrm{E}) + (b + \mathrm{E}) - (a + b)}{2}$$

21. What is meant by an earth fault ? What is meant by "connection to earth" in regard to an electric supply system ?

22. How would you obtain a good earth ? What might be the result if there were several motors all connected to one "earth" and it were defective ?

23. Explain the general principles upon which the position of a fault in an underground cable can be localized.

24. Show how the position of a fault between two insulated underground wires can be found by means of a test with a Wheatstone bridge when a third wire is available for the purpose.

25. Having found that an earth fault has occurred on one underground main, how will you localize the exact spot by means of a loop test, supposing that you had a second main available for the purpose of the test ?

26. What are the difficulties that arise in localizing a fault in an underground cable, to what are they due, and how are they best met ?

27. Sketch the construction of any arrangement which will enable you to detect an "earth" fault on either main of an electric supply network.

28 Describe instruments for detecting leakage or "earth" on the mains from a central station : (a) when the current supplied is continuous ; (b) when the current supplied is alternating.

29. You are required to measure the strength of an electric current flowing in a circuit, in amperes. State exactly how you will do it ; and describe fully the principles on which the apparatus you use is based.

30. Sketch the details of any good form of commercial instrument for measuring electric currents, and mention the conditions which

ought to be fulfilled by such an instrument, and the essential qualities it ought to possess.

31. Describe the working parts of an inspectional ammeter suitable for a switchboard. State whether the deflection of the pointer will be proportional to the current or not, giving reasons.

32. Describe a form of ammeter suitable for use as a sub-standard for calibrating commercial ammeters of different ranges.

33. What is the approximate value of the resistance of a moving-coil ammeter suitable for measuring 250 amps.; how would the instrument be arranged to do so, and how is a uniformly divided scale obtained on this type of instrument?

34. The moving coil of a permanent magnet instrument has a resistance of 10 ohms, and requires a current of 50 milliamperes to give a full-scale deflection. Calculate the value of the shunt required to enable the instrument to read currents up to a maximum of 50 amps. Explain how the final accurate adjustment would be made. *Ans.* 0·01001 ohm.

35. Describe the construction and action of a soft-iron ammeter. If 500 ampere-turns are required to operate it, find the number of turns necessary for (*a*) a 25 ampere range ammeter, (*b*) a 500 volt range voltmeter having a resistance of 20 ohms per volt.

Ans. (*a*) 20, (*b*) 10.000.

36. You are given a commercial ammeter, intended for large currents, to standardize and calibrate. Describe the arrangement you would employ, and explain how you would propose to do it, if it were d.c. and if a.c.

37. Explain the construction and action of Siemens' electro-dynamometer, and show why the current is proportional to the square root of the scale-reading.

38. Can an electro-dynamometer be used for alternating currents? If it may not, state why not; and if it may, show that if calibrated with a direct current it will indicate the virtual value of an alternating current.

39. Describe in detail the Kelvin current-balance, and state what precautions have to be taken to ensure that balances for large currents should read correctly on alternating current circuits.

40. What is generally the difference in construction and use between voltmeters and ammeters of the same type? How would you connect a voltmeter to a lighting circuit to measure the voltage, and an ammeter to measure the current?

41. Why may a change of temperature affect the accuracy of an instrument for measuring potential differences, but produce practically no variation in the correctness of one used for measuring currents? What error is introduced into the reading of ordinary voltmeters by the heating of the coils by the current?

42. Why are low resistance instruments used to measure large currents, whereas high resistance instruments are employed to measure large p.d.'s? If a high resistance instrument, arranged to measure the p.d. between two points in an electric circuit, was replaced by a low resistance one, what would now be measured by it? *Ans.* The short circuit current, which would be inversely proportional to the resistance between the points.

43. Mention the principles on which the action of different types of voltmeters is based, and state the conditions for which each type is most suitable.

44. Describe, with sketches, some form of moving-coil permanent magnet type of instrument, and show how it is used to measure voltage and current. What are the advantages and disadvantages of this kind of instrument as compared with other common types ?

45. Describe, with sketches, some form of voltmeter suitable for a 220-volt direct current circuit. What sort of resistance may be given to a voltmeter used with a single accumulator ?

46. Describe the construction of a good form of commercial voltmeter suitable for use on an a.c. system of about 200 volts, and some form of ammeter of a type which does not depend on the magnetization of iron.

47. Describe in detail, with sketches, a good form of soft-iron voltmeter suitable for measuring either direct or alternating pressures, and point out the errors usually met with in such instruments when used on d.c. and a.c. circuits respectively.

48. It is desired to measure a p.d. of 500 volts, and the only voltmeters available are two which read 110 and 440 volts respectively. How would you connect them up, and what would each read if their resistances were 1,000 and 4,000 ohms ? Would the measurement be practicable if the resistance of the 110-volt instrument were 1,500 ohms ? *Ans.* 100 and 400 volts. No, because p.d.'s would be 136 and 364.

49. Name any voltmeters you know of that can be used for both direct and alternating-current work without any modification, and say why such is the case.

50. What are hot-wire instruments ? State in what respects a hot-wire ammeter differs from a voltmeter of the same type.

51. What are the special advantages and disadvantages of electrostatic voltmeters as compared with current voltmeters ? Say why electrostatic instruments are so well adapted for the measurement of very high pressures.

52. Give sketches illustrating details of construction of a hot-wire and an electrostatic voltmeter. What kind of errors would you look for in testing these two types of instruments respectively ? Describe the operation of some form suitable for measuring voltages from 100 to 250 volts.

53. What are the relative merits of hot-wire, electrostatic, solenoid-and-core, and induction voltmeters for 200 and for 2,000 volts. What special arrangements, if any, must be employed when they are used on alternate circuits ? Have you any reason for adopting one of the types ?

54. What are the sources of error in most ordinary forms of instrument which you would look out for if you were given a voltmeter to report upon, and how would you proceed if laboratory apparatus were available but not an instrument calibrated in volts ?

55. Describe the instruments you would select for (*a*) measuring the pressure across a d.c. lamp circuit of 240 volts ; (*b*) testing the condition of a secondary cell ; (*c*) indicating the busbar voltage in

a 6,600 volt a.c. station ; (*d*) a voltmeter on a very long pilot-wire from a 100 volt a.c. network ; (*e*) ascertaining the p.d. on the plates of a large charged condenser.

56. What is a wattmeter and what does it measure ? Describe the construction of some form of the instrument and explain its use.

57. State whether the reading of a d.c. wattmeter is likely to be affected by reversing both the current and potential circuits. Describe how such an instrument can be calibrated without using the full power which it is designed to measure.

58. Explain the principle of action of any form of practical power meter for measuring electric power expended in an a.c. circuit, and state what are the important points to be attended to in its construction and use when the power factor may be considerably less than unity.

59. Show what corrections must be made to eliminate the error arising from the inductance of the fine-wire coil of an electrodynamometer wattmeter. How is such an instrument affected by the presence of masses of metal in supports of coils or in its external case ?

60. Show how a wattmeter is connected up to measure the power put into the primary of a static transformer. How can a dynamometer wattmeter be compensated for the loss in its pressure coil ?

61. How would you calibrate a wattmeter, using Clark standard cell, potentiometer, volt-box, and standard resistance capable of carrying the maximum current of the circuit for which the wattmeter is required ?

62. Certain primary cells are given you with the request that you will compare their e.m.f.'s and internal resistances. What instruments will you require and how will you proceed ? How would you measure the internal resistance of a secondary cell ?

63. Draw up, briefly, a schedule of rules and conditions to be fulfilled by consumer before you will connect his circuit to the public mains.

CHAPTER IX

FIELD MAGNETS AND ARMATURES

For principles see Chapter IV, and for further information see Chapters X and XV

271. DYNAMOS AND ALTERNATORS. When a conductor is moved in any magnetic field, across the lines of force, an e.m.f. is set up in the conductor, this e.m.f. giving rise to a current if the conductor forms part of a closed circuit. This is the principle of all dynamos or "d.c. machines," and alternators or "a.c. machines." Such may be defined generally as machines for developing electromotive force by the movement of coils of wire in magnetic fields, or by the movement of magnetic fields about coils of wire. The conductors in which the e.m.f.'s are generated are sometimes carried by the moving portion of the machine, and sometimes by the fixed portion. Dynamos generally are of the former, and alternators of the latter class. A dynamo provides for itself the magnetic field in which the conductors, referred to, rotate. In an alternator, this field is provided by means of current from an outside source.

The form of dynamo generally referred to as an "engine-type" generator is designed for coupling up to the crank shaft of the driving engine, a flywheel being interposed to secure steadiness in running. Machines which are designed for driving by steam turbines, which run at very high speeds, are described as turbo-generators; and such are subdivisible into turbo-alternators and turbo-dynamos, according as they generate alternating or direct current.

272. A DYNAMO consists essentially of three parts—

(*a*) The **field-magnet,** which furnishes the magnetic field in which the armature rotates.

(*b*) The **armature,** which consists of coils of wire mounted on an iron core. This is rotated in the magnetic field of the field-magnet, and thus has electromotive forces induced in its coils.

(*c*) The **commutator,** an arrangement whereby the electromotive forces (which are developed in alternate directions in the armature coils as they pass the N. and S. poles of the field) are rendered unidirectional, and thus give rise to a direct current in the external circuit.

An alternator has also a field-magnet and an armature, but, in place of a commutator, collectors or slip-rings, consisting simply of insulated metal rings mounted upon the shaft, are employed. Thus, when the armature coils were mounted on the rotating portion, they were connected to these slip-rings, and the currents were collected from the latter by means of brushes. Since, however, the armature currents of an alternator do not need commutation, and for other reasons, which are both electrical and mechanical, the armature coils of such machines are now always mounted on the stationary part of the machine, the field-magnet forming the rotating portion. In this case, the slip-rings on the shaft are used for leading the *exciting current* into, and out from, the coils of the field-magnet.

It will be evident that direct-current machines are really alternators whose currents are sent in one direction, or rectified, by means of a commutator. The dynamo is a *reversible machine*, that is to say, it may be used either as a dynamo or as a motor. In the first case, the machine is driven by an engine or turbine, and gives out electrical energy. In the second case, electrical energy is imparted to the machine or a current is passed through it from some external source, and the armature is set in motion, the machine then acting as an electric motor. Hence the term "d.c. machine," which indicates a dynamo or a direct-current motor, but does not distinguish between them.

273. SIMPLE ALTERNATOR. In Fig. 352, *a b c d* is a simple coil of wire of one turn, fixed to the spindle *s*, by means of which it may be rotated in the magnetic field **N S.** Each of the ends of the coil is fastened to an insulated metal ring *r* on the spindle, and against these *slip-rings* press the *brushes* *B′* *B*, which lead the current to the external circuit. Suppose that the coil is in the position shown, and that it is given a half turn in the direction indicated by the arrow. One half *a b* of the coil will descend across the field, while the other half *c d* will ascend; and the induced electromotive forces will give rise to currents from back to front in *a b*, and from front to back in *c d*. The electromotive forces in the halves of the coil will thus act together,

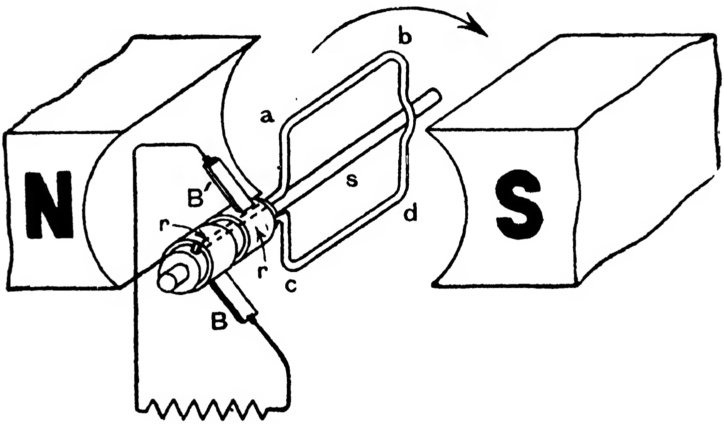


FIG. 352.—SIMPLE ALTERNATOR.

and a current will flow round the external circuit from the brush *B′* to the brush *B* When the coil has made one half-turn, that is, when *a b* is at the bottom and *c d* at the top, *a b* will begin to ascend across the field to its first position, while *c d* will descend The induced electromotive forces will then be in a direction from front to back in *a b*, and from back to front in *c d*; that is, in the opposite direction to the first e.m.f.'s. A current will consequently flow round the external circuit in the opposite direction, viz., from *B* to *B′*. Thus it will be seen that for every complete revolution of the coil, two currents, in opposite directions, will be sent round the external circuit; and if the coil be continuously rotated, an alternating current will be set up.*

The ends *a c* and *b d* of the coil will have no e.m.f. induced in them, as they merely slip between the lines of force, and consequently do not cut them. The length of wire which cuts lines of force is "active," and that which does not is "inactive." The term *active wire* or *active conductor* refers to those portions of an armature coil (or coils) which are instrumental in generating e.m.f. Thus, referring to the

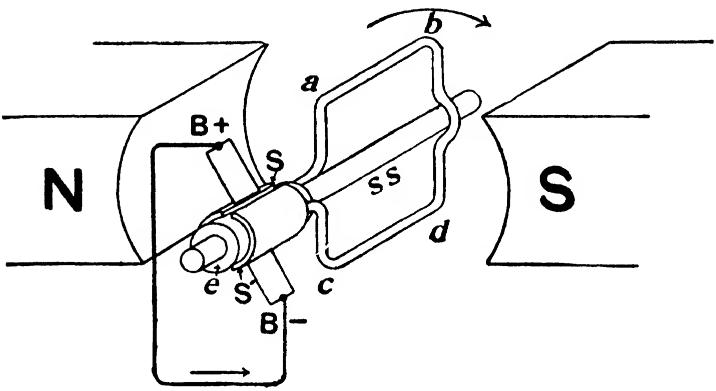


FIG. 353.—SIMPLE DYNAMO.

coils in Figs. 352 and 353, the portions *a b* and *c d* are active; while *a c* and *b d* are inactive.

274. SIMPLE DYNAMO. Fig. 353 represents a simple coil of wire *a b c d*, capable of rotation on the shaft *s s* in the magnetic field between **N** and **S**. The ends of the coil, instead of being joined up to slip-rings, are connected to the halves of a split metal tube. These are mounted on the spindle, but are insulated therefrom and from each other by means of the boss *e* of insulating material. This arrangement is called a *two-part commutator*; and the brushes are arranged so as to press on diametrically opposite

* See Chapter XIII for curve of e.m.f. produced by a simple alternator.

points of it, to ensure that they shall not both be in contact with the same *segment* of the commutator at the same time.

Starting with the coil in the position shown in the figure, and rotating it in the direction indicated by the large curved arrow, an electromotive force will be induced in the direction from back to front in *a b*, and another e.m.f. from front to back in *c d*. These e.m.f.'s, being in the same direction round the circuit, add their effects. This will continue while the coil is making one half-turn. As during that time the end *a* of the coil is connected through segment *S* of the commutator with the brush *B* +, while the other end of the coil is connected with brush *B* – through the segment *S′*, a current will flow round the external circuit in the direction shown by the straight arrow.

Directly the coil begins its second half revolution, an electromotive force will be induced in the opposite direction; but it will be seen that when the direction of the e.m.f. changes, the connection of the coil with the external circuit is reversed by means of the commutator; the brush *B* + being then in contact with *S′*, and the brush *B* – with *S*. The resulting current therefore flows round the external circuit in the same direction as the previous current. As soon as the coil regains its first position, the commutator once more reverses its connection with the outer circuit. The induced alternating current in the armature, therefore, becomes a direct current in the outer circuit, owing to the commutator reversing the connections between the coil and the outer circuit when the induced e.m.f. reverses.

In actual commutators the brushes are fixed radially, and are thus suitable for either direction of rotation. The large number of copper segments are insulated one from another by thin sheets of mica, this being slightly undercut below the surface of the commutator, to prevent the mica from scoring the relatively soft carbon brushes.

In Figs. 352 and 353, a coil of but one turn is shown for the sake of simplicity; but an increased e.m.f. may be obtained by having a coil of several turns, and joining its two ends to the slip-rings or to the commutator, for this increases the total length of conductor acted upon by the lines of force.

275. MODEL DYNAMO. The previous figures illustrate principles in the simplest manner; practical machines are necessarily complex in design. Fig. 354 illustrates a model dynamo on the principle here described, but having a coil of many turns wound on an iron core shaped like a shuttle.

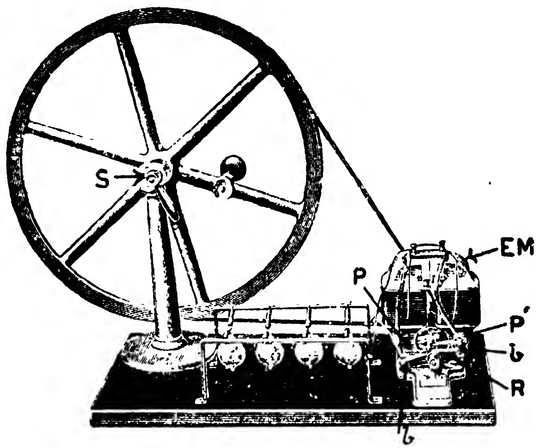


FIG. 354.—HAND DYNAMO.
(*Crypto.*)

This kind of armature, known as the *shuttle armature* (Fig. 355), is a great favourite with amateurs because of its ease of construction, but it is not now employed in practical machines.

EM is an electro-magnet, which is made in two pieces for convenience in winding, these being bolted together at the yoke. The magnet is provided with pole-pieces **P P**, which are so shaped as almost to enclose the armature. The iron core of the armature is not solid, but is built up of thin iron stampings or core plates **CP**, which are threaded side by side on to the steel spindle of the machine, and are tightly clamped together between a fixed shoulder on the further end of the shaft and the nut **N**. The coil is connected with a two-part commutator **C** mounted on the insulating boss **B**. The brushes are held in the brush-holders *b b*; the latter being supported on, but insulated from, the rocker *R*, which allows of their being adjusted at the correct position on the commutator.

The machine is *self-exciting*, that is to say, it furnishes the current for its own electro- or field-magnet. When a dynamo is first run, it is necessary separately to excite its field-magnet by direct current from a separate source.

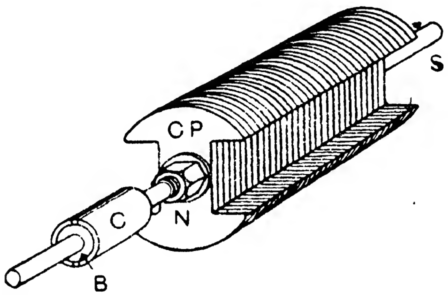


FIG. 355.—IRON CORE OF SHUTTLE ARMATURE UNWOUND.

After having once been excited, however, the field-magnet will retain a certain amount of magnetism. This residual magnetism provides a weak field, and the armature in revolving consequently generates at first only a weak current; but as this current is led round the field-magnet, it increases its magnetism, and so provides a stronger field, and the armature therefore generates a stronger current. And so the process goes on, until the field-magnet gets excited to its full strength.

The machine is shunt wound, that is to say, the ends of the field-magnet coils, as well as the brushes, are connected with the same pair of terminals, which are fixed on the top. From these terminals wires are led to two bent pieces of brass, between which are slung some small low-voltage incandescent lamps, representing the load circuit, or consuming devices.

276. FIELD-MAGNETS. Dynamos may be divided into three classes, according to the form of, or number of poles on, their field-magnets—

(*a*) Single-magnet (or single horseshoe). Two-pole.

(*b*) Double-magnet (or double horseshoe). Two-pole.

(*c*) Multipolar. Having more than two poles.

A *single-magnet dynamo* is one in which the armature revolves between two salient poles N and S, due to a horseshoe magnet. The single-magnet dynamo, of the type

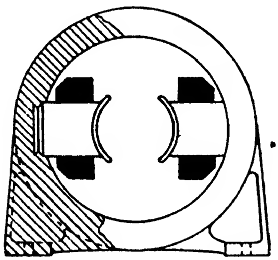


FIG. 356.—FIELD-MAGNET FOR TWO-POLE DYNAMO.

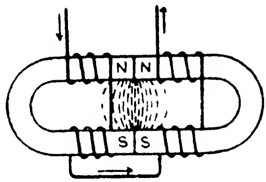


FIG. 357.—CONSEQUENT POLES.

shown in Fig. 354, is now obsolete except for very small machines.

A *double-magnet machine* is one in which two consequent poles are employed. Fig. 356 shows a pattern of present-day field-magnet of this type. A *salient pole* may be defined as a single pole. A *consequent pole,* on the other hand, is formed by the junction of two or more like poles. Thus, if two horseshoe electro-magnets be placed with their like poles together, as in Fig. 357, consequent poles will be formed.

Reasons for discarding the single-magnet form of machine were: (1) the leakage in the magnetic circuit; (2) want of compactness; (3) the difficulty of enclosing the machine, i.e. covering in the ends of the armature and the commutator;

(4) the inefficiency of all but small sizes ; (5) the difficulty of winding and insulating two-pole drum armatures.

The rotating magnets, or rotors, of turbo-alternators have salient poles when they run at comparatively low speeds.

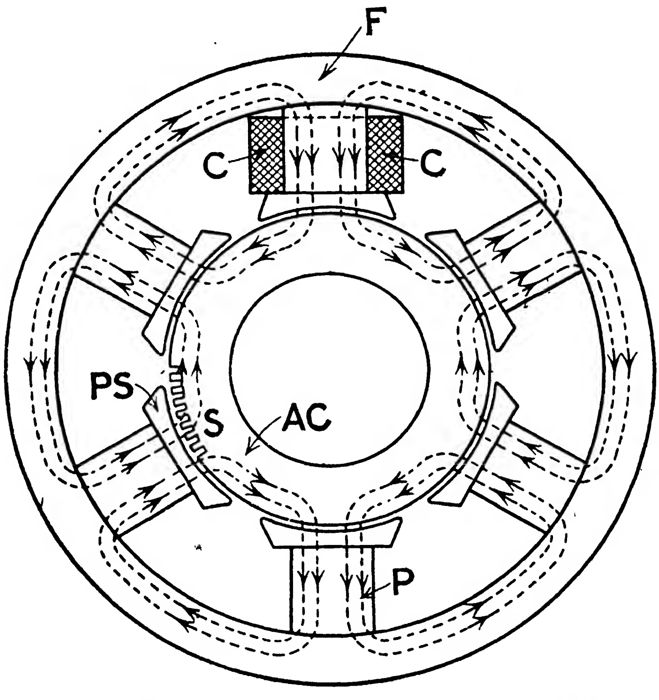


FIG. 358.—MAGNETIC CIRCUITS OF A SIX-POLE D.C. MACHINE.

For high-speed rotors the winding is not heaped up or piled on the core in one place, but is wound in slots so as to give a uniformly increasing strength to the poles, from the edge of the field to the centre or axis. This is called a *distributed winding*, and illustrations of it will be found in Chapter XV.

Largely for mechanical reasons and cheapness of construction, frames of dynamos are now made of circular form with the magnet-cores and poles projecting radially towards the armature. Fig. 358 gives a general idea of the disposition of the field in a 6-pole machine.

Here **F** is the frame of the machine, this acting also as a large yoke to complete the inner magnetic circuits of the poles. **P** is a pole, **PS** a pole-tip or pole-shoe, **C** a coil, **AC** the armature core, and **S** a few of the slots thereon. Considering the direction of the magnetic lines, it will be seen that the top pole is N, and those on each side of it are S; while the bottom pole is S, and those on each side of it N. The poles are thus alternately of N and S polarity. If a few extra lines be imagined, it will be evident that the pole-tips assist the curvature of the fields; and also that it is not necessary to have a very great depth of iron in the core. The air-gap, that is to say, the distance between the surface of the core and the faces of the poles, should be as small as possible.

FIG. 359.—LAMINATED POLE-CORE.

277. FIELD-POLE CORES. The poles of field-magnets are very often laminated, as well as the armatures; and an example of such is given in Fig. 359, each core being secured to the frame by two bolts passing through from the outside. The protruding *pole-tips* serve to hold the coils in position. Sometimes the pole-cores, after being built up, are cast into the frame, and the coils are then put on from the

FIG. 360.—LAMINATIONS FOR FIELD-POLES.
(*Sankey & Sons.*)

front and secured by *pole-shoes,* which are likewise provided with tips.

The main function of the pole-tips is to spread out the flux of lines from the pole as they enter the air-gap between the pole and the armature core, and so reduce the reluctance at this point. The lines curve out from the pole on either side, and the pole-tips facilitate this. Two forms of pole lamination with fixed tips are shown in Fig. 360, one being provided with a ventilating slot. The circular holes are for the riveting together of the plates when they are assembled to form the pole-core.

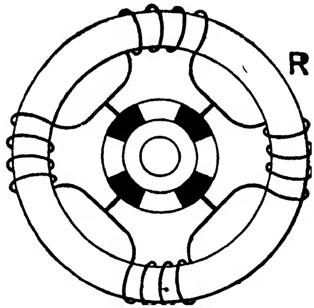


FIG. 361.—FOUR-PART RING ARMATURE.

As an armature rotates, the current-carrying conductors thereon, and the wavering of the lines from the poles as the armature teeth pass by, both tend to induce currents in the iron of the poles if they are solid. But this is stopped by the lamination, and heating and waste of energy are prevented. Sometimes the pole-shoe only is laminated. Many machines, nevertheless, are built with solid cores; these are cast in one piece with the frame.

278. ARMATURES. Dynamo armatures were formerly divisible into two principal classes: (*a*) ring, and (*b*) drum. *Ring armatures* were those in which the coils were wound around and through a ring built up of annealed-iron plates or wire; this ring being supported on some kind of a frame carried by the shaft of the machine. The ring armature will be briefly described, as it was the first practical armature to be devised.

A *drum armature* is one in which the coils are laid from end to end in slots upon the face of a cylinder or drum, which is built up of discs of annealed iron and fixed upon the armature shaft. Of these two kinds of armature, the drum is now invariably used in modern machines.

The principle of the ring or Gramme armature is illustrated in Fig. 361. R is a ring, built up by clamping together a number of annealed soft-iron pieces shaped like very large washers. This part is called the armature core ;

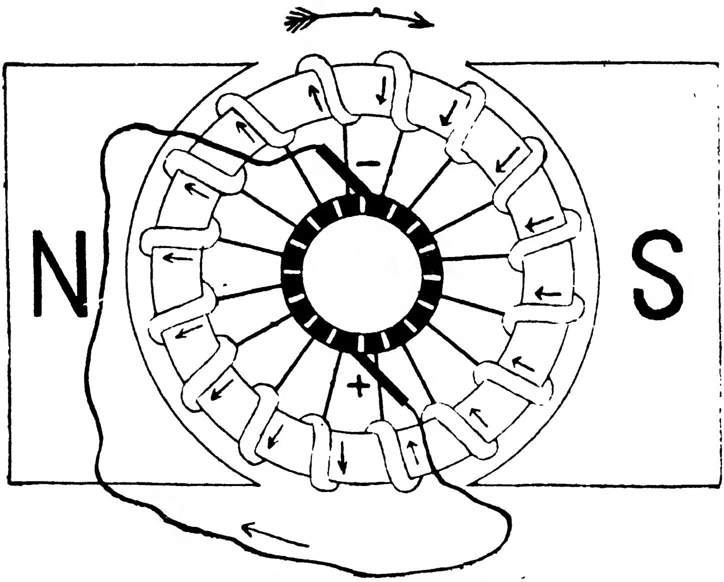


FIG. 362.—CIRCULATION OF CURRENT IN A RING ARMATURE.

the method of fixing it to the shaft is omitted for simplicity. Only four coils are shown, whereas in reality the whole of the core would be covered with coils. The end of one coil is joined to the beginning of the next ; and the junction between each pair of coils is connected with a separate commutator segment. The number of commutator segments is equal to the number of coils on an armature of this kind. These segments are shown black in the figure, the white spaces between being insulating material.

In Fig. 362 a ring armature with a few coils (with only one turn drawn on each) is shown. At any instant the current due to the e.m.f. in all the coils on the right-hand side is flowing downwards, and such also is the direction of the current in the other half.

If the brushes be removed from the commutator, the total e.m.f. in one half of the armature will always be equal in magnitude and opposite in direction to the total e.m.f. in the other half, and no current will flow round it if such is the case. But if the outer circuit be connected, through the medium of brushes and commutator, with those parts of the armature where the e.m.f.'s. of neighbouring coils oppose, the halves of the armature will act together in parallel, and a current will flow round the external circuit.

Since only those parts of the ring-armature conductors that actually cut the magnetic field have e.m.f. induced in them, it follows that only those portions of the turns which lie on the outside of a ring armature are of any use electrically. The inside portions, as well as those on the ends, merely make connection from one "active portion" to the next, there being practically no magnetic field inside the ring. Hence there is necessarily a large amount of wire which is of little service to the armature.

279. LAMINATION. If the iron cores of armatures were made solid, their revolution in the magnetic field would cause currents to be induced in the core as well as in the coils; and these currents would circulate in the core. Such *eddy currents* would be detrimental: (*a*) Their generation would absorb a great deal of energy, and would make the dynamo all the harder to drive; while (*b*) they would heat the core so much as to injure the insulation of the coils.

For this reason the core is always built up of thin *core-plates* of soft iron, in such a way that the iron is continuous in the direction of the lines of force, but discontinuous in the direction in which the eddy currents would tend to be set up, i.e. at right angles to the lines.

In Fig. 363, *a c* is a shaft and armature core, without any slots or coils, supposed to be revolving in the field between the poles. The primary object of the core is to afford the lines an easy path from the N to the S pole, and this object is attained, for the iron is continuous in that direction. The iron is discontinuous, however, in the direction parallel with the shaft and at right angles with the lines of force of the field, i.e. the direction in which there is a tendency for eddy currents to be induced. The core-plates are made of specially manufactured steel sheets of, say, 0·0164 inch thickness. Each lamination is either varnished on one side or else covered with a thin sheet of tissue paper. By these means, the generation of eddy currents in the core is prevented.

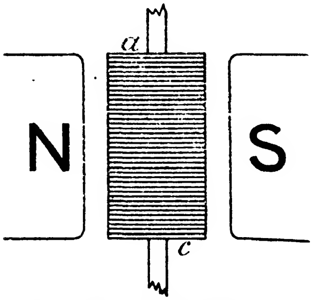


Fig. 363.—Lamination of Armature Core.

An unslotted core is shown, as the cross lines of the slots would confuse the figure ; but in practice the core would be slotted. These slots break up the iron path of the magnetic lines to a certain extent, but they are not made deeper than is absolutely necessary for the reception of the coils.

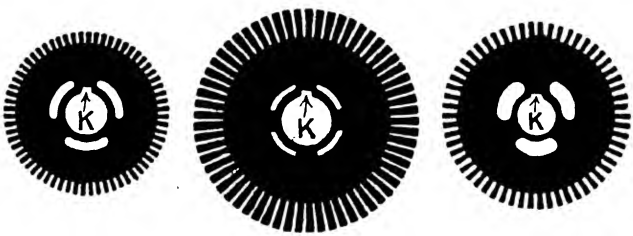


Fig. 364.—Forms of Core-plate for Drum Armatures.
(*Sankey & Sons.*)

280. ARMATURE CORES. Small and medium size cores are built up of a number of discs of soft iron with radial slots punched round the edge ; and Fig. 364 shows various forms for *keying* directly on the shaft, the key slots being shown at K K. The radial slots in each core-plate become channels longitudinally, or parallel to the axis, when the plates are assembled. The openings in the plates are for the ventilation of the core, air channels being formed from end to end of the core when the plates are together.

Although the face of the armature does not touch the pole-pieces as it revolves, there is a considerable strain on it, owing to the reaction between the induced currents in the armature coils and the magnetic fields; the latter exerting a magnetic drag on the coils which tends to stop

FIG. 365.—LAMINATIONS FOR ARMATURE CORE-SEGMENTS.
(*Sankey & Sons.*)

their rotation, in accordance with Lenz's law. If the coils and core-plates were not fixed firmly, this "drag" would cause both to slip round. Thus it is that special care must be taken to mount the plates securely upon the spider, or the shaft. The core-plates or core-segments are punched with teeth round the edge, forming slots parallel with the shaft when the core is built up; the coils being laid in these slots, it is impossible for them to shift.

Large armature cores differ from the smaller sizes in having each core-plate made up of several pieces or segments, which are dovetailed to fit round the periphery of a spider or frame of large diameter (Fig. 365).

A cast-steel spider is illustrated in Fig. 366. A cast-iron ring fits on the spider and carries the core of the armature. The ring has a number of dovetailed grooves into which the dovetail projections on the core-segments fit. The form of these segments, and the method of building up the core, are well shown in Fig. 367, where it will be seen that the teeth on the core-segments form the slots in which the coils are afterwards laid. When the core has been built up to a sufficient height, a massive iron ring is put on. The latter is secured by a number of bolts passing through holes in the core-segments and through the main ring; the whole thus being clamped firmly together.

FIG. 366.—CAST-STEEL SPIDER.

Fig. 368 shows the ring and bolts by means of which the core is held together on the main ring, and the armature is there shown with nearly all its coils in position. The ends of the coils, which may be seen hanging downwards, are afterwards connected to the commutator, which, however, is omitted from the figure.

Round the outer edge of the core will be noticed five circular lines or rings. These are really *air spaces* which are left at intervals after a certain number of layers of core-segments have been put in place. Their purpose is

FIG. 367.—BUILDING UP A LARGE ARMATURE CORE.

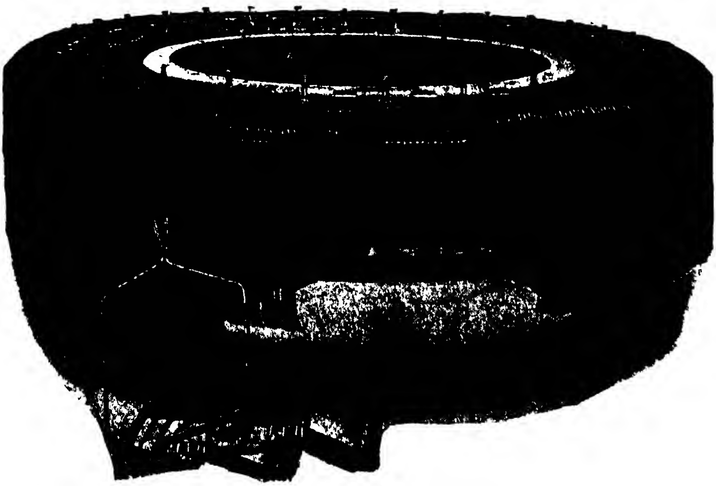


FIG. 368.—LARGE ARMATURE CORE WITH NEARLY ALL ITS COILS IN POSITION.

to allow of the *ventilation of the armature*, the air finding its way through them, and serving to keep both the core and the coils cool when the machine is running.

In some machines the armature core-plates are dove-tailed and fixed into a cast-iron spider, which is keyed to the shaft, and an extension of the lower part of the spider forms the hub of the commutator. Thus the usual practice of having these parts separate is improved upon, and greater strength is secured.

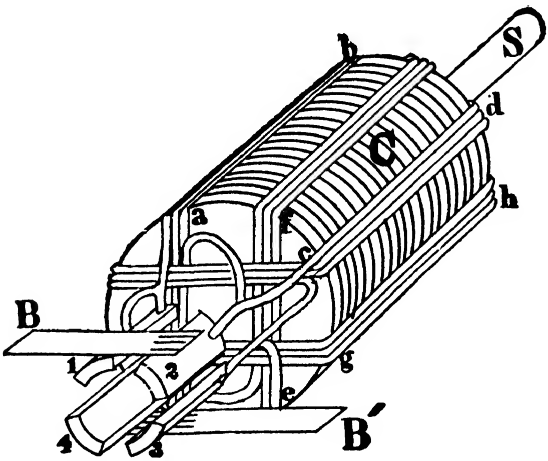


FIG. 369.—ELEMENTARY DRUM ARMATURE FOR TWO-POLE FIELD.

281. THE DRUM ARMATURE has no inside turns of wire; in other words, its coils or conductors are disposed on the outside of the core. This will be understood from Fig. 369, in which a very elementary drum armature with four coils is depicted. Here *S* is the shaft (the front end of which is cut away to show the commutator segments more clearly) and *C* is the core, which is made up of thin soft-iron plates. The insulating supports for the commutator segments 1, 2, 3, 4 are not shown, and the core-plates are much exaggerated in thickness. The figure illustrates a *smooth* (i.e. unslotted) *core*, and only four coils are shown for the sake of clearness. In an actual armature, however, the whole surface of the core would be slotted, and the number of coils and commutator segments would be very much greater. Starting from segment 1, the coil *a b* makes three turns, and finishes at segment 2. From this starts the coil *c d*, finishing at segment 3. Between segments 3 and 4 is the coil *e f*; and between segments 4 and 1 the fourth and last coil *g h* is connected. Thus it will be seen, as in the case of an ordinary ring armature, the end of one coil and the beginning of the next *in order** are connected with the same commutator segment. There is thus a complete circuit through all the coils.

Fig. 369 shows the correct disposition of the coils for a two-pole field, and is moreover an elementary example of a lap winding. The reader will notice that the halves of any given coil (say *e* and *f*) are not disposed on diametrically opposite parts of the surface of the core. The chief reason for this is that the coils could not be conveniently arranged round the core. Another is that the front and back connections would have to curve round the shaft *S*, the front end of which is omitted from the figure. If the halves of the coils were diametrically opposite, or nearly so, the amount of idle wire at each end of the core would be sensibly increased.

Fig. 370 illustrates a hand-wound armature, that is to say, one in which the turns of wire are laid in their slots, one after the other, by hand. This method of winding is very laborious, and is only adopted with very small armatures. Practically all armature coils are *former-wound*, being separately wound on special *formers* (mounted in winding machines) which give them the exact shape required. The coils are then individually bound up and insulated ready for placing in the armature slots. After they are so placed, the connections between coil and coil and between the coils

* As will be understood better later on, the "order" of the coils on a drum armature is not so simple as in the case of a ring armature. Thus, in a drum armature, coils which are connected to neighbouring commutator segments do not lie next to one another on the core. In a ring armature they do.

and the commutator are made, the insulation is finished off, and the coils secured.

A consideration of the simple two-pole drum armatures (Fig. 369) will make it clear that each coil must be so disposed on the core that, when active, one side is in front of the N pole and the other in front of a S pole. Thus the end-connections (or portions passing across at each end of the armature) have to be very long, approximately equal to the diameter of the armature core. This means a considerable amount of idle wire, and also considerable bulging at each end of the armature where the connections cross and recross each other. Such bulging is illustrated in

FIG. 370.—SMALL HAND-WOUND DRUM ARMATURE FOR TWO-POLE FIELD-MAGNET.
(*Metropolitan-Vickers.*)

the small armature in Fig. 370, and is only to be avoided by the use of complicated end-connectors, or by using an armature of great length and small diameter. Another drawback of a two-pole armature is the difficulty of insulating neighbouring wires or connectors with high p.d.'s between them.

The above-described difficulties are amongst the chief reasons why four-pole machines are much more common than two-pole machines for ordinary sizes; and why six, eight, and ten or more poles are employed for machines of large size. Another reason is that, for a given output, a two-pole machine is generally bulkier and heavier than one with four or more poles.

In Figs. 371 and 372, which show four- and six-pole field-magnets, *h h′* are the halves of a coil, and *c* the front connecting wire between them, the commutator and the connection thereto being omitted. From these figures it will be obvious that, with armatures of a given diameter, the amount of idle wire in the coil of a four-pole armature is much less than that in a two-pole one, and that in a six-pole armature it will be still less.

The modern drum armature consists of a laminated annealed-iron ring or cylinder with a number of slots running across its face and conductors disposed therein. It may be traversed by air-cooling channels. It would be built up of disc core-plates, as in Fig. 364. In large sizes

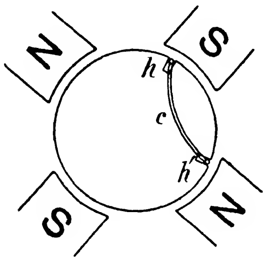


Fig. 371.—Connection of Coil of a Four-pole Armature.

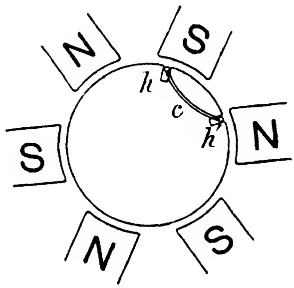


Fig. 372.—Connection of Coil of a Six-pole Armature.

the core is built up of segments, as shown in Fig. 365. Consequently, the ring or cylinder is hollow; it being unnecessary to carry the iron core right down to the shaft, as it has merely to provide a sufficient depth of iron to carry the magnetic lines passing between adjacent field-poles.

The armature conductors (in which e.m.f. is induced as they pass in front of the various poles, and which may consist of wire or strips of copper, according to the current to be carried) are laid in the slots on the face of the core. The methods in which they are connected to one another and to the commutator are numerous, and only first principles can be dealt with herein. In fact, the "winding" of an armature, or in other words, the proper calculation, disposition, and interconnection of the conductors thereon, is a matter requiring considerable specialist knowledge.*

The method of preparing coils followed by most dynamo builders is to wind them on "formers" of the exact shape and size of each particular coil; this "former" being so fixed as to be capable of rotation, and the wire or strip wound off a neighbouring spool or drum. For any armature, the shape of the coil depends on three dimensions only. Thus, in Fig. 373—

(i) The length of the active sides *a a* of the coil. This

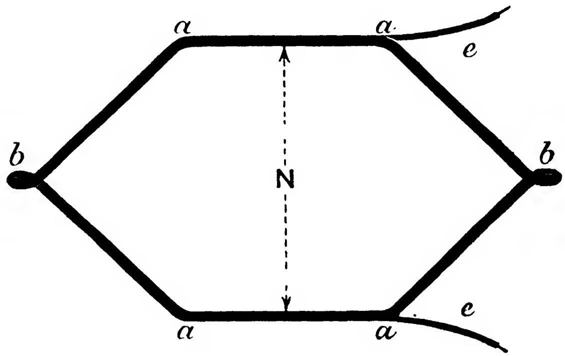


FIG. 373.—ARMATURE COIL.

is equal to the length of the armature core including the end plates, plus from ¾in. to 1½ in.

(ii) The length of the inactive portions *a b*, which depends on the pole pitch.

(iii) The breadth of the coil N, which is very nearly equal to the pole pitch.

The coils—when wound—are bound round with insulating tape, and (the naked ends being first cleaned and tinned) are then ready for mounting on the armature core. In

* A full explanation of the various methods of winding armatures is much beyond the scope of this work. The subject is naturally of the utmost importance to the dynamo designer and builder. Various works have been devoted to the subject, some of which are given in the list at end of Vol. II. See, for example, *Practical D.C. Armature Winding*, by L. Wollison. (Pitman, 7s. 6d.)

Fig. 373, *e e* are the ends of the coil, these being shown shorter than they would be in reality.

282. MOUNTING OF COILS. In Fig. 374 is shown a small armature core mounted on its shaft ready for "winding," and the toothed *end-plates* between which the core-discs are compressed should be noticed. Before the coils

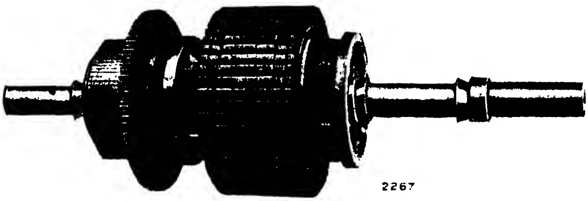


FIG. 374.—D.C. ARMATURE CORE READY FOR WINDING.
(*Crompton.*)

are put into position the slots are carefully cleared from "burr" or sharp projections of metal; and are then each provided with an insulating lining of varnished "fuller-board" or "press-spahn," or some other special insulating

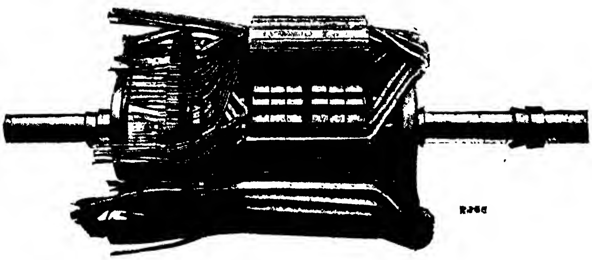


FIG. 375.—PARTLY-WOUND ARMATURE.
(*Crompton.*)

material somewhat akin to very tough cardboard, impregnated with an insulating varnish. In Fig. 375, which shows a partly-wound armature, these linings or "cells" are clearly shown. In this figure many of the coils are already in position, with their ends let into the slots in the commutator lugs, ready for soldering thereto.

Small and large finished armatures are shown in Figs. 376 and 377 respectively. When the winding of an armature is

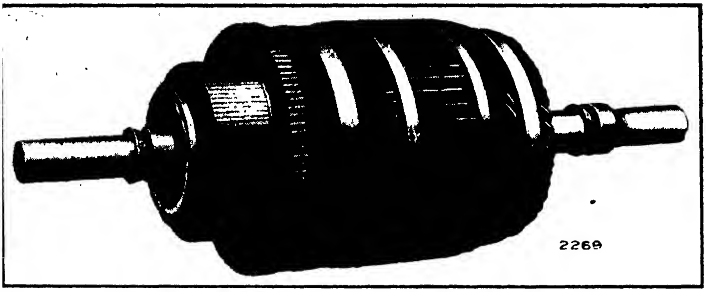


FIG. 376.—FINISHED SMALL ARMATURE.
(Crompton.)

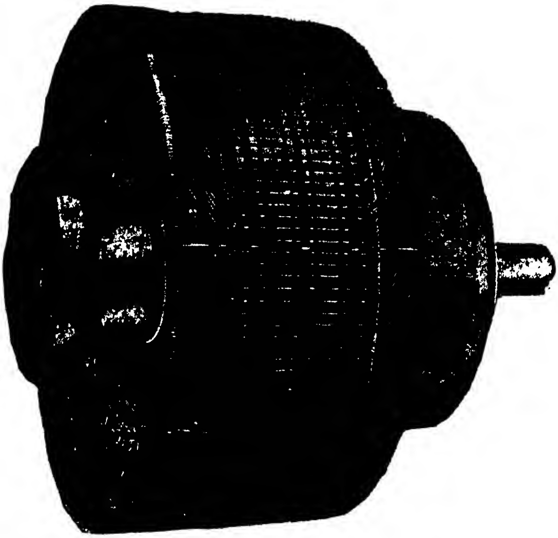


FIG. 377.—FINISHED LARGE LAP-WOUND ARMATURE.
(Lancashire Dynamo & Motor Co.)

finished, it is necessary to bind or fix the coils in position to prevent them bulging out from their slots under centrifugal force. A common method of doing this is to wind two or three bands (each consisting of several turns) of binding wire (of steel or phosphor bronze) around the surface of the core, in shallow grooves previously turned therein, these bands being finished off and strengthened by soldering. Another method is to use core plates or segments with teeth slightly widened at their tips. The overlapping of the extremities of the teeth allow wooden wedges to be driven in between these projections and the tops of the coils, the latter being thereby securely held in place.

Besides this binding or wedging on the core itself, the extremities of the coils, where they project from each end of the core, are tightly bound round with insulating material and wire.

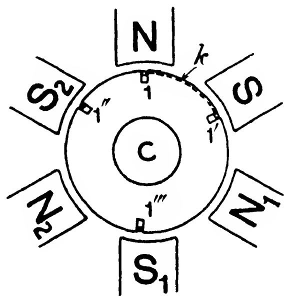


FIG. 378.

283. ARMATURE CONDUCTORS. The e.m.f. induced in an armature may be increased, (*a*) by the use of a greater length of active wire, (*b*) by revolving the coil at a greater rate, and (*c*) by strengthening the magnetic field.

Fig. 378 gives an end view of a six-pole field and an armature core in that field. Now if 1 be a single conductor thereon, it will be evident that the direction of the e.m.f. induced in it will be changed six times in each complete revolution. If the rotation of the core were clockwise, the e.m.f. would be in a direction from front to back while passing in front of a *N* pole, and from back to front while passing a *S* pole. The commutator **C** is at the end of the core facing the observer, and as there cannot be any external-circuit connections at the other end of the core, it is necessary to connect the far end of 1 with the end of some other conductor. Further, it is essential that that second conductor should be in such a position on the core, that when 1 is under a *N* pole the other shall be under a *S* pole, and vice versa.

Thus we might connect it with 1′, 1″, or 1‴. To avoid long connections we should connect 1 behind with either 1′ or 1″, let us say 1′, as shown by the dotted line *k*.

In Fig. 379, *N S N* are the faces of three adjacent poles, and 1 and 1′ our first and second conductors, as they would appear *if the observer were lying along the shaft* of the machine and the armature core were removed. If we connect 1 and 1′ by a connection *k* at the far end of the core, it will be clear that when they are passing *N* and *S* poles respectively the e.m.f.'s will be induced in the directions shown by the arrows. These e.m.f.'s will be reversed while 1 and 1′ pass *S* and *N* poles respectively, as in the

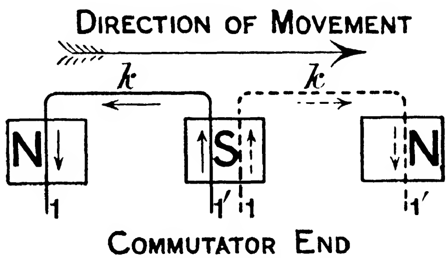


FIG. 379.

dotted portion of the figure. Thus 1 *k* 1′ constitute a coil of a single turn, the halves 1 and 1′ always assisting each other in the generation of e.m.f.

An armature coil may consist of one turn, or a number of turns, of insulated conductor formed-up and bound together. The number of turns and size of the conductor depend upon the required e.m.f. and output of the machine; and on other matters which are affected by manufacturing and commercial considerations. In large machines the coils may consist of one or two turns only, such armatures being sometimes termed *bar wound*; thick copper bars being bent so as to fit closely into the armature slots leaving room for the necessary insulation. These thick conductors are laminated to avoid the generation of eddy currents therein.

In the following diagrams, to render them simpler, each coil is indicated by one turn only, but they may consist of a number of turns. A turn is made up of two bars or straps interconnected at the ends.

284. ARMATURE WINDINGS. The question now arises, how is the coil depicted in Fig. 378 to be connected to neighbouring coils and to the commutator ?

In Fig. 380, 1 and 1′ are the ends of the coil, and 2, 2′ and 3, 3′ the ends of two neighbouring coils. The dotted

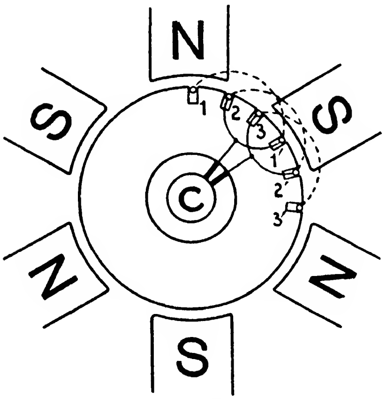


FIG. 380.

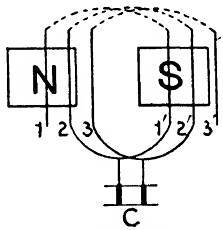


FIG. 381.

lines represent the connections at the back end of the armature, and the firm lines those at the commutator end ; the radial lines representing connections to the segments of **C**. If the connections be traced, it will be found that the path of the circuit is from 1 to 1′, 2, 2′, 3, 3′, etc., as shown in Fig. 381, which, like others that follow, is termed a **development diagram** ; the pole-faces, armature conductors, etc., being laid out on a flat surface. It will be observed that, as we follow the winding round the armature, we lap or loop back from the end of one coil to the beginning of the next. This is called a **lap winding.**

In Fig. 382, 1 and 1′ represent as before the ends of the first coil; we might connect the end 1′ of the first coil with the beginning of a coil farther round the core, the end 2′ of this second coil being joined-up to the beginning 3 of a third coil still farther on. We could thus travel round and round the armature without turning back, until all the coils were connected. This is known as **wave winding.**

Fig. 383 represents a six-pole machine with a **lap-wound armature.*** Here the active halves of the coils are numbered 1, 1′, 2, 2′, 3, 3′, 4, 4′, etc.; the bends at the back or pulley end of the armature being denoted by the dotted lines, and the front bends and connections to the commutator C, by firm lines.

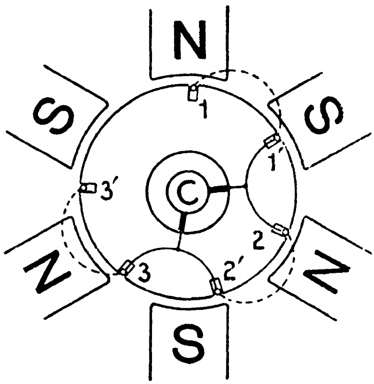


Fig. 382.—Wave Connection of Armature Conductors.

In the first place, it should be noticed that the coils overlap one another. That is to say, starting at 1 and proceeding to 1′, the connection *k* carries us back to 2, and *k′* back from 2′ to 3, and so on.

Another manner of representing this winding is shown in Fig. 384, where the armature core, commutator, and field-frame are to be imagined as cut through at a point *p*, and then flattened out, with the face of the core K and commutator C facing the observer; with the field-poles *above* the figure, the field-poles being indicated by dotted circles. The outside turns on the number or top end of the core in Fig. 384 are those at the pulley end of the armature, while those shown between the core and the commutator are those at the commutator end.

The connections to the commutator C are indicated by the vertical lines; and the positions of the brushes are

* Figs. 383 and 384, and other diagrams not in the text, are on folding plates between pp. 550 and 551.

shown at **B** +, **B** –, etc., the + and – brushes being connected together in two groups to the + and – terminals, **T** + and **T** –. The ends *a a*, *b b*, and *c c*, of the winding are really adjacent, and are connected together when the core is its proper shape.

285. WAVE-WOUND ARMATURE. Fig. 385 shows a four-pole wave-wound armature, the slotted face of the core **K** being bent-up all round (so to speak) so as to face

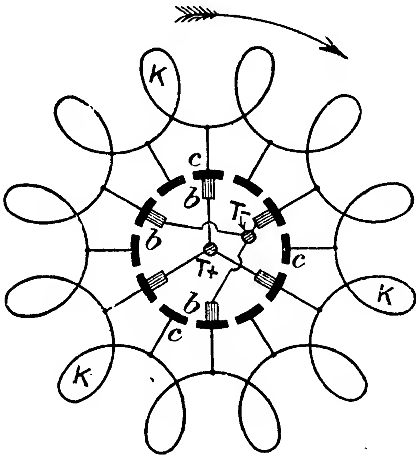


FIG. 386.—PARALLEL CIRCUITS THROUGH A SIX-POLE LAP WINDING.

the observer. This bending-up apparently makes the core-slots radiate from the centre, whereas of course they lie parallel with each other round the surface of the core.

Here it will be seen that, starting at any point *p* in the winding and following the circuit line round the core, the conductor describes a zigzag or wavy path.

In comparing lap and wave windings, important points of difference will be found. If (in the case of a *lap winding*) the path of the current be traced through the armature from the – to the + terminal, it will be found to split up into two, four, six, or eight **parallel paths,** according as the machine has 2, 4, 6, or 8 poles ; the number of parallel paths thus being *equal to the number of poles.*

In proof of the above statement, if Fig. 383 or 384 be traced out, the result will be as depicted in Fig. 386, there being six parallels through the windings. In this figure, the coils K K K, etc., are shown without overlapping, and their connections to the commutator segments *c c c* are indicated. Starting from the negative terminal, it will be found that there are six paths to the positive terminal, each consisting of two coils in series. When the armature has moved round farther so that the brushes come into contact with those segments that at present are free, there will still be six parallel groups of coils, but half the coils will have left one group and entered another.

With a *wave winding,* on the other hand, whatever the number of poles, there are always only **two main parallel circuits** or paths through the armature windings. Thus if we start from the top B + brush in Fig. 385, and trace out the circuit through each slot, a diagram may be got similar to Fig. 387. It will be seen in Fig. 385 that the two brushes B – and – B – are connected to the two commutator segments between conductors 3 and 8, and 13 and 18 respectively ; while the two + brushes are in connection (through three segments) with the conductors 7, 12, 9, 14, 17 and 4. The lower brush + B is in connection with two commutator segments, thus giving the state of things shown at the top of Fig. 387 ; but inasmuch as the conductors 9 and 12 are only partly active—and in equal and opposite senses—they may be assumed to neutralize each other's effect. Further, as a moment later the + brushes (Fig. 385) are in connection with the commutator segments between conductors 7 and 12 and 17 and 4, the dotted connection *k* (Fig. 387) then disappears. In practice the total number of conductors is so much greater that there are many more lying in the spaces between the poles.

Broadly speaking, a multiple-circuit or lap winding is adopted in machines of 100 kw. and over, and in small machines for low voltages only. A two-circuit or wave-winding, on the other hand, is generally employed when high voltage and a moderate current are required for small machines.

286. LAP AND WAVE WINDINGS. Starting with a two-pole machine, a given strength of pole, a given number of turns in each armature coil, and a given speed ; the enlarging of a multiple circuit or lap-wound armature to suit a four, a six, or an eight-pole field will not increase the e.m.f. of the machine. What will be increased will be the number of parallel circuits in the armature—in direct proportion to the increase in the number of poles—and a consequent proportionate increase of the total current. With a two-circuit or wave winding the exact reverse will be the case. That is to say, any increase in the number of field-poles will give an increase of total e.m.f. in proportion to the number of pairs of poles added ; the current (with a given number of turns per coil) remaining the same.

In each case (multiple circuit and two-circuit), it is assumed that the number of slots and coils (or conductors) on the armature is increased so as to correspond with the increase of poles.

In a multiple-circuit machine the extra coils go to form extra parallels, and extra brushes and commutator segments are required. In a two-circuit machine, the extra conductors are divided-up between the existing two circuits ; and the extra commutator segments serve to keep the p.d. between neighbouring segments the same as before.

The effect of increasing the number of poles of a given bi-polar multiple-circuit machine is the same as would be obtained by connecting as many machines in parallel with the original as there were pairs of poles added. With a two-circuit machine, the effect of increasing the number of poles is exactly the same as would be obtained if we doubled, trebled, or quadrupled the strength of the existing poles ; or placed as many machines in series with the original as there were pairs of poles added.

Although the armature of a machine may be quite central to start with, that is to say, although the air-gaps between the pole-faces and the armature core may be equal all round, it does not follow that the conductors in the core slots are at uniform distances from the surface. Thus the e.m.f.'s generated in the armature conductors may be slightly unequal at different points, even though those points may be similarly situated with regard to their respective poles. Further, the field-poles themselves may not be of equal strength, owing to slight differences in the permeability of the cores. Now when a machine has been running a little time, the bearings inevitably begin to wear, and as the wear continues the armature will get out of centre. When this occurs, the air gaps at the top poles will increase, and those at the bottom poles will decrease; and the generation of e.m.f. at different points round the armature will inevitably become unequal, even if the pole-strengths and conductor depths be uniform.

One great advantage of wave over lap winding is that the above-mentioned inequalities have absolutely no effect in the former case. Each of the two circuits of a wave winding is made up of a number of conductors under *all* the poles; and as unequal generation of e.m.f. affects both circuits alike, there is no want of balance in the armature and its e.m.f. as a whole is not affected. With a lap or multiple-circuit winding the various circuits are acted upon by different poles at any given moment, and if the armature be out of centre, some circuits will be generating more e.m.f. than others. The effect of this will be to cause unequal division of the current in the armature, and sparking at the brushes.

It is sometimes very useful to be able to tell at a glance whether a finished armature is wave- or lap-wound. Where the connections at each end of the core slope in *opposite* directions it indicates a wave winding, whereas where they slope in the *same* direction a lap winding is indicated.

287. MULTIPLEX WINDINGS. The windings already described are termed *simplex*, to distinguish them from other forms of multiple-circuit windings, which may be *duplex* or *triplex*. Multiplex windings consist in combining two or three distinct sets of coils on the armature, and doubling or trebling the number of commutator segments. Thus the conception of a *duplex multiple-circuit* armature may be obtained by imagining two exactly similar armatures, and the result of taking the coils and commutator

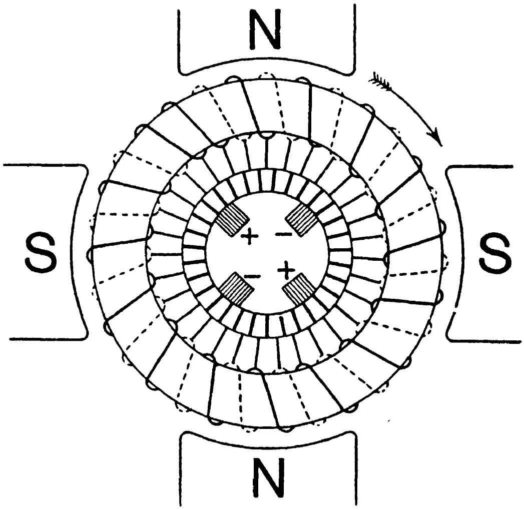


FIG. 387A.—DUPLEX MULTIPLE-CIRCUIT ARMATURE

segments off one and sandwiching them between the coils and segments of the other. If a winding of this kind were represented by means of such a diagram as Fig. 383, the figure would be very intricate; but the ring-armature diagram in Fig. 387A will make things clear.

The object of a multiplex winding is to enable an armature of a given size, and with a given number of slots and size of coil conductor, to supply more current than it would if the slots were filled up with one series or set of coils. If a simplex-wound multiple-circuit armature were dismantled and wound duplex, its e.m.f. would be halved and its current doubled. Thus the kilowatt-capacity would be identical in each case.

An ordinary or simplex two-circuit (wave) winding can be duplexed or triplexed in much the same manner as a multiple-circuit winding. In this case also the result would be a corresponding increase of current capacity and decrease of voltage, the kilowatt capacity remaining as before.

Although a good deal of space has been devoted to the matter of armature winding, only the outlines of the subject have been touched upon. Those who desire a closer acquaintance, and especially those who are in any way concerned with the design, winding, or repair of direct current armatures, cannot do better than consult the works mentioned in the list at the end of Vol. II.

288. COMMUTATORS vary in detail with different makers. Generally speaking, however, every commutator is much the same ; consisting as it does of strips of hard-drawn copper arranged in the form of a drum or cylinder, with mica or micanite insulation between the strips ; the latter being fitted with slotted lugs to allow of the connection of the armature conductors.

In Fig. 388 (folding plate) are shown the details of construction of a small commutator. The left-hand figure is a view of the face with the top half in section ; while the right-hand illustration is an end view, with the right half in section. The different portions are described by an index to the component parts.

It will be noticed that each commutator bar is so shaped that it dovetails into the projections formed by the large end of the bush **B** and the collar **CC**. The micanite insulation between is generally formed of three pieces. viz., a sleeve **M′**, and two V-shaped collars **M** and **M**. Micanite is built-up of small pieces of scrap mica stuck together with shellac varnish. When heated, micanite can be moulded into any shape. It will be evident that when **CC** is drawn in by tightening-up the set-screws **SS**, the commutator segments **C** will be clamped firmly in position.

An important modification in the form of the commutator on high-speed dynamos (such as turbo machines, made by Metropolitan-Vickers), is that the segments have pieces which project radially outwards so as to form what looks like a protruding flange, and the brushes press against the side of this instead of the cylindrical surface. Vibration, on a radial commutator, does not tend to throw the brushes off the contact surface, which is a very practical advantage compared with the ordinary form.

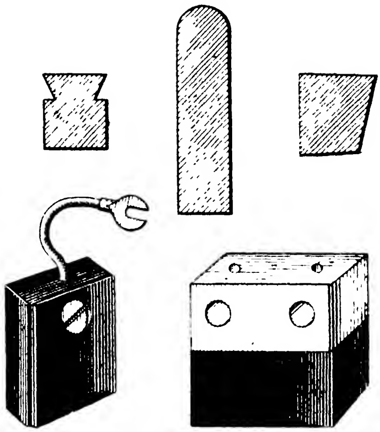


FIG. 389.—FORMS OF CARBON BRUSH (*Le Carbone.*)

289. BRUSHES. The term *brush* is a survival of the days when bunched copper wires were used for collecting the current from commutators. Carbon has superseded copper as the material, and the "life" of commutators has been greatly lengthened in consequence; the commutator of a machine with carbon brushes, properly looked after, presents a highly-polished smooth surface.

Carbon brushes represent the wearing and renewable part of the contact gear between the fixed and revolving parts of the circuit through an armature, and naturally require to be held in position. This is done by means of brush-holders.

Brush-holders are carried by a bracket from a rocker which slides in bearings secured to the frame of the dynamo. Each brush-holder contains a number of carbon brushes, the pressure of which upon the commutator may be individually regulated by means of springs. The tension of each of these springs is adjustable so that the radial arm which presses upon the top of the brush may keep it in contact with the commutator. Each brush has a length of braided flexible wire firmly attached to it by means of a screw-headed bolt and nut passing through the top of the carbon, as seen in one of the brushes in Fig. 389, or by being moulded into the carbon. The eyelet ends of these flexible wires or pig-tails are clamped to the brush-holder by means of screws. When a brush is thinly copper-plated it slides easily in its brush-holder box.

Fig. 390 shows a type of brush-gear. In this case *box-type* brush-holders are used. The carbon brush slides in a " box " which itself is rigidly fixed in position, the brush being pressed down the box on to the commutator by means of a spring bearing on its upper end. In the *lever holder*, which is the older pattern, the brush is rigidly clamped in the extremity of a holder which is pivoted at one end.

Referring to Fig. 390 (folding plate), which shows side and end views of the brush-gear for a four-pole machine, B is a box holder, and A the arm to which it is clamped. A is bolted to one of the arms A′ of the rocker R ; but is insulated therefrom by a bush and two washers W of insulating material. *b* is one of the brushes, and S the spring which keeps it bearing on the commutator C. Each brush has a flexible wire F fastened to it, and by means of this permanent connection is made between the brush and its holder. The commutator has a groove G turned on the armature side, to permit the brushes being brought right up to its edge, and even wear secured. The four brush-holders are joined-up in pairs by the connectors K K ; and the cables leading to the main terminals of the machine are soldered into the thimbles T T.

290. BEARINGS. All modern machines are fitted with self-oiling, or ring-bearings. Fig. 391 gives a simple example ; *B* is the bearer lining, *R* a gun-metal or brass ring hanging on the shaft in a slot cut in the top half of the bearing. The lower half of the bearer-housing *H* forms a reservoir for the oil, in which the bottom portion of the ring dips. As the shaft rotates, the ring revolves slowly and takes up oil with it. The shaft is provided with oil-throwers or ridges *R′* inside the bearer-housing, which throw off superfluous oil by centrifugal force, and prevent creepage along the shaft.

A section of a six-pole machine, showing shaft, bearings and frame is given in Fig. 392 (folder). *F F* is the frame and *P P* two of the poles. *S* is the shaft, and *S′* the spider on which the armature core-plates *C C* are mounted. The plates are compressed between one end of the spider and the end ring *E E*, the whole being held together by the bolts *B B*. *A A* indicate an air-gap left in the centre of the armature core for cooling purposes; the air being drawn in at each end of the spider, and passing out through the gap. This air-gap is formed by inserting "distance pieces" to keep the core-plates apart.

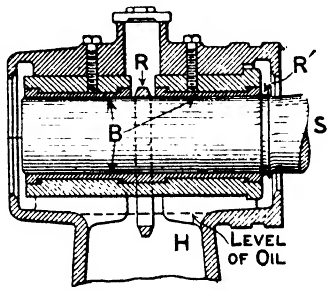


FIG. 391.—SELF-OILING OR RING-BEARING.

The commutator hub *H* is bolted to the spider at *B′ B′*; and the commutator segments *S S* are held in position by the end ring *E*, *E* and the bolts *b b*. *F′ F′* are two of the field coils, and the position of the armature winding is shown at *W W*. *Be Be* are the two bearings, and *P* the end of the shaft which carries the pulley.

Having briefly described the principal features of construction, we will turn to what happens when an armature of a dynamo is rotated in its field.

291. THE INDUCED E.M.F., due to the motion of a conductor across a magnetic field, depends upon the cutting of lines of force, and its amount varies with the rate at which the lines are cut. The term "lines of force" is used here because, in a dynamo, the conductor can only cut lines when these pass through or across an air-gap.

The simplest case is that of a straight conductor moving at a uniform velocity across, and at right angles with, a magnetic field, as in Fig. 81. If it moves at a steady rate of 1 cm. in each second, and if it cuts 1 line of force in each cm., the induced e.m.f. between the ends of one cm. length of the conductor is one c.g.s. unit.

It is necessary to begin all calculations of induced e.m.f.'s by taking c.g.s. units. It must be remembered that the volt is merely a convenient multiple of the c.g.s. unit, and has been selected quite arbitrarily to suit the needs of practical men who desire to save time and avoid long rows of figures or other forms of symbolic expression. As the volt is merely 10^8 or 100,000,000 c.g.s. units of e.m.f., any expression giving absolute values in such units can be converted to volts by dividing by 10^8. Bearing this in mind it is simpler to always work out the foundational problems in absolute units and accordingly eliminate one factor from equations.

The area swept over by a conductor of 1 cm. length in 1 sec. is 1 cm. in breadth and 1 cm. in length, or 1 sq. cm. The definition of field-strength is the number of lines per sq. cm., so if there is one line per sq. cm. the field is of unit strength. If the velocity V be doubled, twice the number of lines will be cut per second. If the field-strength H be doubled, twice the number of lines will be cut per second; and if the length of the conductor L be doubled, everything else remaining unaltered, the same thing will result.

The simple equation which expresses these facts may be written—

$$\text{induced e.m.f. (c.g.s.)} = \frac{\mathsf{F}}{t} = L \times \mathsf{B} \times V$$

where F is the total number of lines cut in a time t. F/t is therefore the *rate* of cutting lines of force. This indicates that the e.m.f. is directly proportional to (*a*) the length of active conductor on an armature, (*b*) to the strength of the field in lines per sq. cm., and (*c*) to the velocity with which the conductor cuts the lines of force of the field.

With the same value of total flux the e.m.f. generated is the same whatever the length of conductor. The e.m.f.

depends on the length L of the conductor only, when the flux-density **B** is constant in the field cut by the conductor An illustration may help to make this clear.

In Fig. 393 a conductor of a certain length L, shown as 8 cms., is supposed to be moving in the direction of the dotted arrows at such a velocity V, that it traverses the distance and sweeps over the space between $a\ b$ to $c\ d$ in 1 sec. The flux-density **B** is the number of lines in each sq. cm., and the total number of lines cut is $L \times$ **B**. If $a\ b\ c\ d$ be the face of a dynamo-pole then **B** is the flux-density in the air-gap, $L \times l$ = area of the pole-face, and this area $\times$ **B** = the total flux **F**, emanating from the pole.

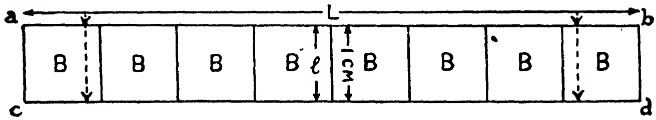


FIG. 393.

At any instant during the time the conductor of length L is moving from $a\ b$ to $c\ d$ it has a definite e.m.f., E, induced in it, and each centimetre has an induced e.m f. equal to **B** $\times V$, so that the total induced e.m.f. (c.g.s.) = $L \times$ **B** $\times V$. If the same total flux **F** were compressed into an area of half the size, L might be halved, but the flux-density **B** would be doubled, so the induced e.m.f. would remain unaltered, providing the cutting velocity was the same.

Another way of dealing with what takes place is to consider the change in the total flux **F**, which is threaded through the electric circuit formed by the conductor and its connections and the time occupied by the change. This gives the **average e.m.f.** induced in the conductor during the time of that change in the total flux. The whole electric circuit considered is $a\ b$ and G in Fig. 81 or $s\ i\ o\ p$ in Fig. 86.

A coil of a single turn of wire, pivoted on an axis at right angles to a magnetic-field, and rotated at a steady speed in a uniform field of flux-density **B**, cuts the lines of force of the field as it revolves. The arrangement would be something like the simple dynamo in Fig. 353.

Suppose the area enclosed by the coil is a sq. cm's. Then the flux **F** passing through the coil when its plane is at right angles to the direction of the field is $a \times$ **B**.

When its plane lies parallel to the direction of the field, the flux passing through the coil is zero. Hence for each revolution of the coil the following changes take place—

Position.	*Result.*			*Change.*
Coil parallel to field.	No lines of force through coil			
Coil at right-angles to field.	**F**	,,	thread coil	+ **F**
Coil parallel to field.	No	,,	through coil	− **F**
Coil at right-angles to field.	**F**	,,	thread coil	+ **F**
Coil back in starting position.	No	,,	through coil	− **F**
	In one revolution, total change =			4 **F**

Hence the number of lines cut in one revolution is 4 **F** for a single turn of wire. The lines cut per revolution will increase with the number of turns N in the coil. The number of lines cut per second will increase with the number of revolutions n through which the coil is turned per second. For a coil of N turns revolved at n revolutions per second, the lines cut per second will be $= 4\,\mathbf{F} \times N \times n$, and as one line cut per second = 1 c.g.s. unit of e.m.f.—

the average induced e.m.f. (c.g.s.) $= 4\,\mathbf{F} \times N \times n$.

Diagrams of armature windings are difficult to depict on paper by perspective drawings. Some convention must be accepted to enable things which are really endless and form parts of a circular body to be illustrated in a diagram. A similar case that must be known to every schoolboy is the representation of a map of the earth. The globe is not flat but an oblate spheroid, very nearly a sphere, so no part of any size can be drawn strictly to scale on a flat sheet of paper, but some well-known and generally agreed dodges permit of the earth's surface being mapped sufficiently correct in proportion to serve the purpose for which they are wanted.

In a similar way the circular fields of dynamos, and the windings on the armatures which run in these fields, can be shown in a developed form, as if they were cut across at a certain place and opened out till they lay flat. A development and extension of a diagram of a drum armature has been given a few pages earlier when dealing with lap-winding, and such diagrams are called into service to explain a good many of the matters which concern us in the further treatment of dynamos in Chapter X.

Let us suppose that Fig. 394 represents a N pole of a

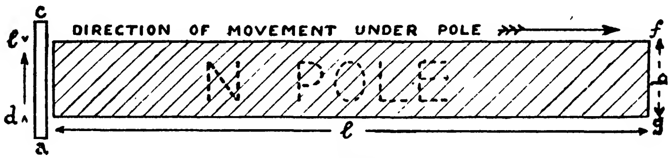


FIG. 394.

dynamo, and that we are looking down on an armature conductor a.c. which is moving in the direction of the feathered arrow under that pole. Then the small arrow indicates the direction of the induced e.m.f. The dimensions of the pole are length l and breadth b. The induced e.m.f. will then depend only upon the total flux emanating from that pole, and the time it takes $a\ c$ to cut that flux.

The conductor which cuts the flux from, that pole has an active length b. Since

$$V = \frac{l}{t} \text{ then } t = \frac{l}{V} \text{ and } \mathsf{F} = l \times b \times \mathsf{B} = \text{area} \times \mathsf{B}$$

$$\text{The induced e.m.f.} = \frac{\mathsf{F}}{t} = \frac{l \times b \times \mathsf{B}}{\frac{l}{V}}$$

$$= \frac{l \times b \times \mathsf{B}}{1} \times \frac{V}{l} = b \times \mathsf{B} \times V.$$

Here b represents the length of the conductor (cutting the lines from the pole in a lengthwise direction), so that we get back to the previous formula.

We can now regard the N pole in Fig. 394 as being bent into a circle so that the edges d e and f g come together and coincide. Outside this there must be a S pole of equal strength so that the magnetic system, looked at sideways, would be something as shown in Fig. 395, which might represent an ironclad or annular magnet, of the type depicted in Fig. 65, turned on its side. The field would then be a radial one, and the conductor inserted in that

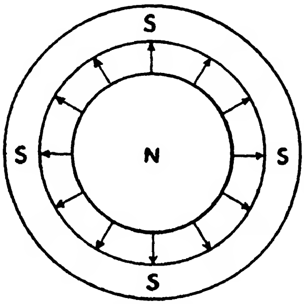


Fig. 395.

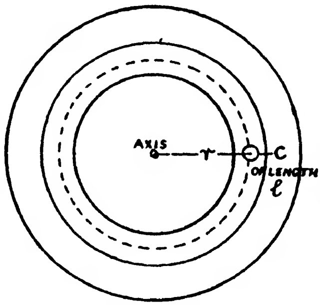


Fig. 396.

air-gap would travel round a circular path between the two poles. The radius of that path of travel would be r, Fig. 396, which shows the end-section of the conductor c whose active length at right-angles to the paper is b, as in Fig. 394. The conductor on moving round its circular path at a uniform velocity V between the two poles with o as the axis or centre, would cut the uniform radial field of **B** lines per sq. cm. at right angles.

The length of the field L measured circumferentially is, since diameter $= 2r$, equal to $\pi \times 2r$; and its breadth, from back to front, is corresponding to the active length of the conductor L, so that the area $= 2\pi r\ L$ in sq. cms. As in the case already considered, the total flux $\mathbf{F} =$ area $\times$ **B**, so in this case $\mathbf{F} = 2\pi r\ L\ \mathbf{B}$. If the conductor revolves n times in a second round the axis o, then V can be expressed in r.p.s. instead of cms. per second, since the length of the circular path is fixed and the motion is cyclic.

$$V = \frac{2\pi r}{t} \text{ for one revolution and } \frac{2\pi r n}{t} \text{ for } n \text{ revolutions.}$$

If n be taken as the revolutions per second, t becomes unity and the induced e.m.f. $= b \times \mathsf{B} \times 2\pi r\, n$, or in words,

length of active conductor × flux-density × cms. traversed per second.

But the length of the active conductor L is the same

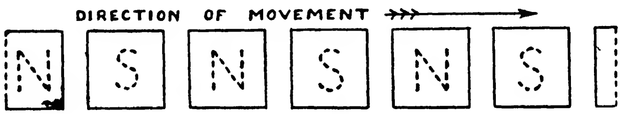


Fig. 397.

as the breadth of the field b, while the total flux is $= 2\pi r\, L \times \mathsf{B}$, so that the equation may be written—

$$\text{induced e.m.f.} = 2\pi r\, L \times \mathsf{B} \times n$$

that is, total flux × r.p.s.

The flux need not be produced by one pole; it may emanate from several poles. Fig. 397 is drawn to the same scale as Fig. 394, but instead of one pole there are six poles, so that it may be regarded as a development of the magnetic system shown in side view in Fig. 358. In this case the average e.m.f. induced in one conductor will be the same as in Fig. 394 if the total flux be the same. The direction of the e.m.f. will be reversed as the conductor cuts the flux first in one direction and then in the other, but as the rate of cutting is the same the magnitude of the e.m.f. will not vary.

The general equation or formula for the induced e.m.f. in a dynamo is written in many ways according to the symbols preferred and their exact significance. If the reader turns up half-a-dozen textbooks or pocket books, as many different formulae may be found. They all mean the same thing however. It has been shown that the factors necessary are flux cut, conductors cutting, and rate of cutting. Therefore in every formulae there must be symbols representing each of these quantities.

The total flux is made up of the flux from each pole × the number of poles. The number of poles is equal to 2 × pairs of poles.

The armature conductors, or, as they are sometimes called, face or external conductors, make complete turns over the armature, hence 1 turn = 2 conductors. Then there are two methods in which the conductors can be connected up to one another. They may make two parallel circuits between the points on the commutator where the brushes make contact, or they may have as many circuits in parallel as there are single poles. The former is called wave-winding and the latter lap-winding. The e.m.f. at the brushes of a dynamo is the aggregate of the several e.m.f.'s in the conductors in series between the segments where the brushes rest. Hence it is not sufficient to have the total number of conductors stated; we must also know how that total number is connected. The number in series will be total number/number of parallel paths or circuits through the armature.

The speed may be stated in revolutions per minute or revolutions per second. In the former case the figure must be divided by 60, as r.p.s. are what we used to work with. It simplifies calculations to work with r.p.s. straight away.

The equation for the induced e.m.f. (volts) in a dynamo may be stated in the following terms—

$$= \text{Flux per pole} \times \text{No. of poles}$$

$$\times \frac{\text{No. of armature or face conductors}}{\text{No. of parallel paths or circuits}} \times \frac{\text{r.p.m.}}{60} \times 10^{-8}$$

$$= \text{Flux per pole} \times \text{No. of poles}$$

$$\times \frac{\text{Total No. of external conductors}}{\text{circuits in parallel}} \times \text{r.p.s.}/10^{8}$$

= Flux per pole × 2 × pairs of poles × No. of turns in series per circuit × r.p.s. × 10^{-8}

and if p = No. of pairs of poles,

F = flux per pole,

N = total number of conductors on armature,

then, for a lap-wound armature

$$E = 2p \times \mathsf{F} \times \frac{N}{2p} \times \text{r.p.s.} \times 10^{-8}$$

$$= \mathsf{F} \times N \times \text{r.p.s.} \times 10^{-8}$$

and for a wave-wound armature

$$= 2p \times \mathsf{F} \times \frac{N}{2} \times \text{r.p.s.} \times 10^{-8}$$

$$= p \times \mathsf{F} \times N \times \text{r.p.s.} \times 10^{-8}$$

The induced e.m.f. of any given machine, with the number and disposition of the armature conductors already fixed, is therefore proportional to two things only—the total flux and the speed, while the simple formula is—

$$\frac{\text{Total flux} \times \text{No. of conductors in series} \times \text{r.p.s.}}{10^{-8}}$$

= induced volts

292. EXCITATION. We now come to the methods by which field-magnets are *excited*; that is, connected with the armature to provide exciting or magnetizing current in the field-windings. The methods adopted are quite independent of the form or number of poles on the field-magnet of a d.c. machine.

Connection diagrams of the different arrangements are given in Fig. 398—

(*a*) **Magneto machines** are those in which permanent magnets are employed as field-magnets. Very small machines of this type are used for telephone, instrumental, and ignition work. Reference has been made to such generators in connection with magneto-ringers, and hand-generators for portable testing sets, while nearly every internal-combustion engine requires a magneto to fire the explosive mixture.

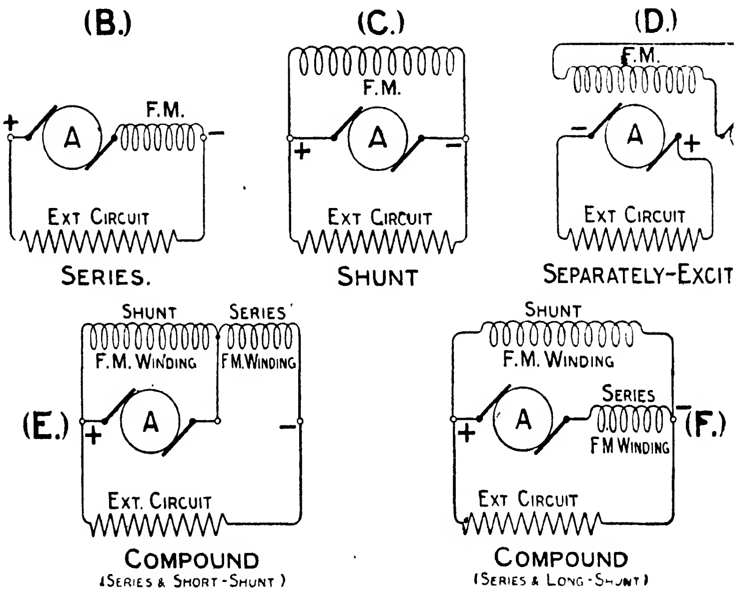


FIG. 398.—METHODS OF EXCITATION OF D.C. MACHINES.

(*b*) In a **series dynamo**, the current, starting from one of the brushes goes first through the field-magnet coils and then through the external circuit. It follows, therefore, that the field-magnet coils must be wound with thick conductor, to enable them to carry the main current.

(*c*) In a **shunt dynamo** the field-magnet coils form a shunt to the external circuit, the current from the armature dividing between the two. The coils must then consist of many turns of comparatively fine wire.

(*d*) In a **separately-excited machine** the current for the field-magnet is furnished by a small auxiliary dynamo which is called the *exciter*.

(*e*) In a **series and short-shunt compound-wound** machine the field-magnet is wound with two distinct sets of coils or windings. One of these consists of a few turns of thick wire, and is in series with the external circuit, so that it carries the main current. The other is of fine wire, and is joined up as a shunt to the armature.

(*f*) The **series and long-shunt compound-wound** method is very much the same as that just described, except that the shunt-winding is in parallel with not only the armature but also the series coil.

It should be obvious, from what has gone before, that series and shunt dynamos must behave differently when the load changes, or the current taken from them is varied from nothing to the maximum the dynamo can give safely. When a series dynamo is providing no current to the external circuit, there is no exciting current in its field-magnet coils. When it is fully loaded up, the coils are carrying the current taken from the armature. Hence the flux produced by the field-magnet will vary according to the magnetization curve of the iron.

Conditions are quite different with a shunt dynamo. Ignoring for the moment certain subsidiary effects, as the field-magnet coils are connected across the brushes—which are, to all intents and purposes, the terminals of the armature—so long as the dynamo is run at a steady speed the current through the coils will not be altered by any changes in the load on the armature; the external circuit being simply a parallel connection to the coils.

As a consequence of these differences in condition of the magnetic circuit, the behaviour of the two classes of dynamos is not alike; and while one is suited for maintaining a constant current in a circuit, the other is adapted for maintaining a constant difference of potential between the conductors of a circuit in which the consuming devices are joined up in parallel.

293. COMMUTATION. The points on a commutator where the brushes should touch are termed the *neutral points*; and they are so-called because the commutator segments passing them are connected with those armature coils in which the direction of the induced e.m.f. is just being changed.

The commutator of a two-pole armature has two neutral points, which lie on diametrically opposite portions of the commutator; that is to say, on an imaginary line intersecting the centre line of the shaft at right angles.

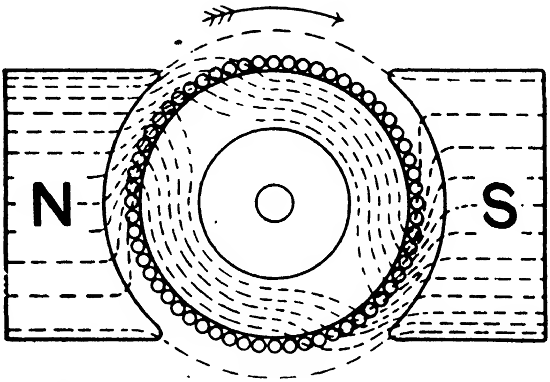


FIG. 399.—DISTORTION OF TWO-POLE DYNAMO FIELD.

The *line* between these points is termed the *diameter of commutation*, and is denoted by *D* in Fig. 400.

In a four-pole ring or lap-wound drum armature there would be two diameters of commutation and four neutral points, and so on.

If the magnetic field kept the same form whether the armature was revolving or stationary, the neutral points on the commutator would lie opposite the centres of the poles in the case of a drum armature. With a ring armature they would lie midway between the poles. The armature, however, becomes an electro-magnet when the induced currents are flowing through its windings, and has consequently a magnetic field of its own. Thus it reacts on and distorts the field due to the field-magnet, and we have what is known as *armature reaction.*

The effect of this reaction (in a dynamo) is to twist the field in *the same direction as the armature is revolving,* as shown in Fig. 399. Consequently the neutral points on the commutator and the diameter of commutation are likewise

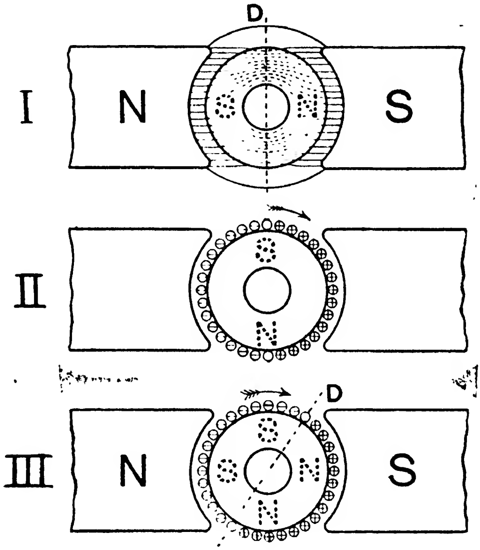


FIG. 400.—DIAMETER OF COMMUTATION OF TWO-POLE RING ARMATURE.

twisted round. The brushes have therefore to be moved forward, otherwise sparking would occur ; and the amount of this movement is called the *lead* of the brushes, or the *angle of lead.*

In Fig. 400,* I shows the magnetization of the core

* The + and − signs in the little circles representing armature conductors are meant to indicate that the currents are flowing outwards and inwards respectively. Another method is to use the signs × and · Then × represents the head of an imaginary arrow and · its point : × denoting an inward and the point an outward current.

by the field-magnet alone, II the *cross-magnetization* due to the armature current alone, and III the combined effect of both; the distortion or twist of the field being approximately as drawn in Fig. 399. The armature of a two-pole dynamo may be regarded as a magnet with its N and S poles set along an axis more or less at right angles with that of the magnetic field of the field-magnet; and that this armature-magnet twists the permanent field in the direction of rotation.

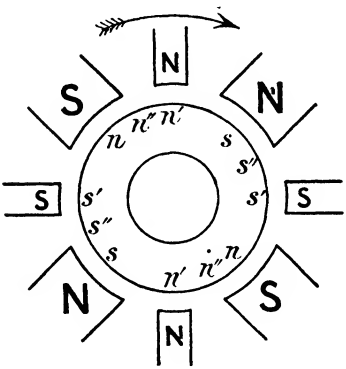


FIG. 401.—ACTION OF INTERPOLES ON FOUR-POLE MACHINE.

It follows that it is very necessary to have a strong field-magnet, so that the reaction of the armature magnetism upon the permanent field may be kept within bounds. Unless the angle of lead be small, the commutation and working of the dynamo is unsatisfactory—for reasons which are discussed in Chapter X. It is mainly because of the absence of commutators that turbo-alternators have reached a much more advanced stage of development than turbo-dynamos.

294. INTERPOLE MACHINES. To oppose the magnetic field set up by the armature, and to help commutation, *auxiliary* or *commutating poles* or *interpoles* are often fixed between the main poles, in such a position that they practically counteract the distorting action of the armature field.

In a field-magnet of this type the coils of the interpoles consist of a few turns of thick wire, which are connected *in series* with the armature. Thus the greater the current that is drawn from the armature, and hence also the stronger the magnetism of the armature and the greater the tendency to distort the main field, the greater will be the opposing field of the interpoles.

In Fig. 401 *N S N S* are the field-poles, *s n s n* are the poles which would be induced in the armature core by the field-poles alone, and *s′ n′ s′ n′* those which would be set-up by the armature currents alone; the resulting polarity (if there were no interpoles) being indicated by *s″ n″ s″* and *n″*. N N S S are the interpoles, and it will be noticed that their polarity is such as to counteract the distorted polarity of the armature by tending to induce a S pole where there is a N pole, and vice versa. These interpoles may, in a sense, be looked upon as the advance guards of the main poles beyond them—in the direction of rotation. Thus if the latter were changed, the interpoles would have to be of opposite polarity, assuming the main poles to keep as indicated in the figure.

295. SPARKING. In an ordinary armature, when the brush is in the act of passing from one commutator segment to another, for a short interval it will be in contact with both, and so will short-circuit the coil connected between them.

Now if the coil be very active, i.e. if it be cutting too strong a magnetic field and generating an appreciable e.m.f., a comparatively large current will flow round it and through the short-circuiting brush. Afterwards, at the moment the brush un-short-circuits the coil, sparking will occur; and this will heat and tear away the points of contact between the brush and the commutator segment.

Or if, on the other hand, at the moment when the coil is being un-short-circuited it is not generating some e.m.f. and carrying a current comparable with that in the coil in front of it (in the direction of rotation), there will also be sparking, owing to the fact that the brush was collecting nearly entirely from that segment which is just leaving it.

To prevent sparking, it is necessary for the brush-rocker to be moved until the proper "lead" is found, i.e. until the brushes touch the commutator segments a little in advance of those connected with the coils which are passing through the neutral position. There is a possibility that the current in any given coil may not be reversed quickly enough under the brush, so that sparking still takes place. The time taken for the current to be reversed is largely dependent upon the resistance of the short-circuit, and is the less the greater the resistance. The armature coils which form part of this short-circuit cannot be made with high resistance; hence brushes having a comparatively high contact-resistance are found to be of value in obtaining sparkless commutation.

296. COMPENSATING WINDINGS. In high-speed machines the armature conductors have to carry large currents; and the cross-magnetization of the armature, and its reaction on and distortion of the field, would consequently be much greater than in ordinary machines were steps not taken to prevent this.

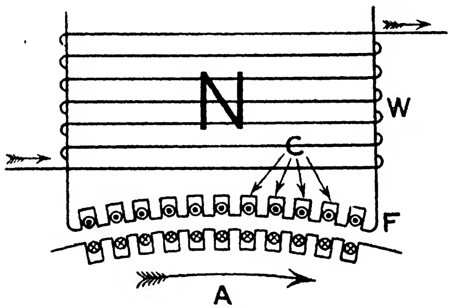


FIG. 402.—COMPENSATING WINDING.

To overcome this armature reaction, a *compensating winding* is employed. This may be regarded as a fixed winding in which the current is always equal but opposite in direction to the armature current. The effect is to neutralize the tendency of the armature currents to magnetize the armature core, and so bring about distortion of the field.

In Fig. 402, **N** is a field-magnet pole and **W** the shunt-winding. The face of the pole at **F** is slotted in exactly the same manner as the armature core **A**, and conductors are disposed in these slots. Further, this compensating winding **C** is so connected that the current in it is always equal but opposite in direction to the current induced in the armature conductors as they pass the pole. The compensating winding is connected in the main circuit of the machine, and the current therein varies in exact correspondence with the current in the armature conductors. The currents in these two windings thus neutralize each other's magnetic field under all conditions, and the cross magnetization of the armature is prevented.

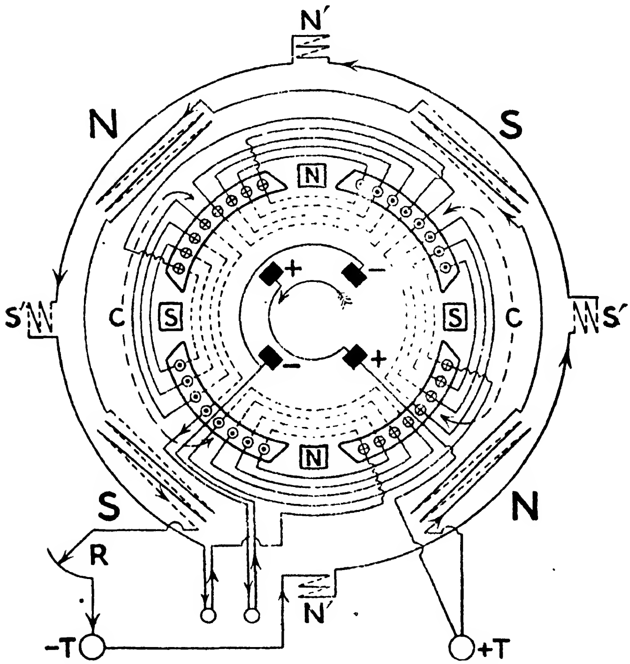


FIG. 403.—WINDINGS OF INTERPOLE COMPENSATED TURBO-DYNAMO.

The reaction in turbo-dynamos is so great that it is desirable to fit them with interpoles, and, in addition, with a compensating winding. The compensating winding in this case is inserted in slots punched in the faces of the pole-shoes with which the main poles are fitted; and its effect, together with that of the interpoles, is to ensure perfect commutation at all loads with fixed brush-positions.

Fig. 403 is a diagram of the fixed windings of a four-pole turbo-dynamo.

Starting from the – terminal – T, the shunt circuit passes through the field-rheostat R, and the field-coils *N S N S* of the main poles, to the + terminal. Starting again from – T, the main or armature circuit first traverses the interpole coils *N′ S′ N′ S′*, then the compensating windings C C, and lastly the armature itself, via the – and + brushes ; and so to the + terminal + T. *N S N S* are the interpoles themselves.

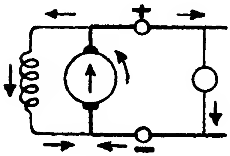


Fig. 404.

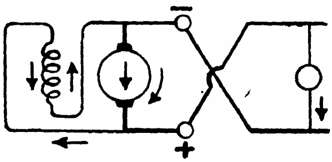


Fig. 405.

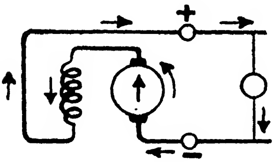


Fig. 406.

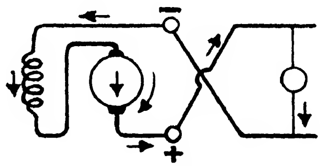


Fig. 407.

297. DIRECTION OF ROTATION. The direction of rotation of a dynamo is usually expressed as *clockwise* or *anti-clockwise*, as the case may be, when facing the bearing-end of the commutator. Generally speaking, when a dynamo is first installed, the direction of rotation of the shaft is given, and the terminals are marked "positive" and "negative," accordingly. What happens if at any time the direction of rotation of a dynamo has to be reversed ? In Figs. 404 and 405 a shunt-wound dynamo is shown, the arrows marking the direction of rotation and the flow of the currents. Connection Fig. 405 shows that when the direction of rotation is reversed, the field leads should be reversed, otherwise the field current would flow round the magnets in the reverse direction and demagnetize them.

In the case of a series dynamo, as Figs. 406 and 407 show, the internal leads from the terminals to the brush-arms have to be reversed in order to prevent reversal and demagnetization of the field. The whole question of the reversal of direction of rotation is of greater importance in the case of direct-current motors, and is dealt with more fully in Chapter XI.

298. FAULTS. The faults which may crop up in dynamos are so many that an enumeration of the chief must suffice.

(*a*) Failure to start generating, owing to brushes making bad contact.

(*b*) Flats on commutator, due to wearing away of one or more segments before the rest and resulting in sparking.

(*c*) Breakage or loosening of connections.

(*d*) Short-circuits or leakage in armature or field-windings or across adjacent commutator segments.

(*e*) Overheating of field or armature coils, due to defective ventilation.

(*f*) Leakage of current across rocker through dirt collecting on it.

(*g*) "Hunting" or unsteadiness of e.m.f., due to working on unstable part of characteristic curve.

(*h*) Breakage of regulator resistance coils

(*i*) Open-circuit in field-winding.

Given a machine from a reputable maker, troubles generally follow from want of reasonable attention, or by sheer carelessness and ignorance. The majority of difficulties can be avoided by cleanliness, and care to the necessary adjustments. Dirt, moisture, and loose connections give rise to more faults and failures than all other causes put together.

Electrical faults can be traced by tests for conductance and insulation. The most troublesome are those which interfere with the running of a machine, but disappear when it is taken adrift. Washers, collets and bushes are relatively weak points which require to be watched, so that by taking tests as each part is dismantled defects can be found in less time than if the mechanical work was gone through without them. Always trace out the circuits before disconnecting any, and be careful to label every end and the terminal or point to which it was connected, so as to be sure of correct reassembling.

299. HEATING. All dynamos become more or less heated in working, this being due to the continuous flow of current in the coils, to the setting up of eddy currents, and to the effects of hysteresis in the armature core. There is a limit to the degree of heating that can be permitted, and in operating machines attention has to be given to their ventilation, so that whatever heat is generated may be dissipated as easily and quickly as possible. The overheating of dynamos is bad, because it increases the resistance of the armature and magnet windings, and so leads to a greater loss of power therein, and, most serious of all, it is harmful to the insulation.

The dynamo-maker, being faced with keen competition, desires to get the maximum output for the least possible expenditure upon material and labour. The tendency, therefore, is to run machines at higher temperatures than used to be thought desirable or safe. This is not to the detriment of the user, as the advent of more stable and durable insulating materials, the better proportioning of ventilating ducts, and the greater knowledge available as to the watts which can be dissipated from each unit area of the surface of coils, permit of much higher temperatures being recognized as standard than formerly. The principal problem in design of electrical machinery may be said to be to get as much use made as possible from each pound of copper put into a machine.

A dynamo can be loaded up until one of three things happen: the mechanical strength of some of its parts may not be sufficient to withstand the strain and a mechanical failure follows, or the heating becomes so great as to endanger the insulation, or the sparking at the brushes becomes excessive.

300. TEMPERATURE RISE. Hot-spots, or particular places in the windings where the temperature is higher than the rest, have to be guarded against with extreme care in winding designs. It is the practice on many large machines to totally enclose them and pass air through under sufficient pressure to cause a steady and abundant flow. Ventilating channels or ducts run through all parts where heat might cause an excessive rise in temperature. A standard figure of 40° C., 45° C., or 50° C. has been selected for different classes of generating plant, and tests are made on completion and before dispatching new machines to ascertain how far they comply with the calculated performance in this respect.

The **temperature tests** are often taken with thermometers poked into all accessible parts, and the temperature rise on a six hours full load run and two hours overload run is ascertained and recorded. Assuming a machine on the test-bed showed a temperature of 63° C. after its test run, starting from cold, if the temperature of the air (say in a hot engine room) be 24° C., the temperature rise would be $63° - 24° = 39°$ C. In such a case, the temperature of the hottest part inside the coil might be as much as 80° C. above that of the air, so that the actual temperature of that hottest spot would be $80° + 24° = 104°$ C. This figure approaches the limit it is safe to allow as a maximum, and it is this maximum temperature inside the coil that determines whether the insulation will deteriorate or not.

Another, and in many cases a preferable method of determining the temperature-rise of a coil, is to make use of the fact that the resistance of metals increases with temperature. That is to say, the resistance of the winding is measured at its first temperature, and again when it has warmed up, and the temperature-rise is calculated therefrom.

It has already been explained that the variation in the resistance of 1 ohm of a conductor at 0° C. when its temperature is altered by 1° C. is known as the *temperature-coefficient* of resistance of that conductor and is generally denoted by a.

From this definition it follows that if a resistance of 1 ohm at 0° C. be increased in temperature by t° C., the change in resistance is at, and the new resistance is $(1 + at)$. Further, if a conductor has a resistance of R_o at 0° C., and has its temperature increased by t° C., its new resistance $R_t = R_o(1 + at)$.

The resistance at 0° C., however, is seldom determined, and what is generally known is the resistance R_1 at a temperature t_1° C. Then if R_2 be the resistance at a higher temperature t_2° C., the above equation can be written—

$$R_2 = R_1\{1 + a(t_2 - t_1)\}$$

$$\text{or} \quad t_2 - t_1 = \frac{R_2 - R_1}{R_1 a}$$

Ex. The resistance of the shunt-winding of a dynamo is 265 and 320 ohms respectively before and after a full-load test, extending over six or more hours. Calculate the temperature-rise of the coils. assuming that they are wound with copper wire.

$$\begin{aligned} \text{Temperature rise} &= t_2 - t_1 \\ &= \frac{R_2 - R_1}{R_1 a} \\ &= \frac{320 - 265}{265 \times 0{\cdot}0043} = 48{\cdot}2° \text{ C.} \end{aligned}$$

The value of the temperature-rise as calculated from the change of resistance is always higher than that registered on a thermometer placed on the surface of the coil. The reason for this is that the temperature rise by resistance is the average value throughout the coil; and since the coil is hotter inside than on the surface, the average temperature is greater than that of the outer layers, and is, therefore, a nearer approach to the maximum temperature in the coil. However, the difficulty of measuring the cold and hot resistances accurately under commercial testing conditions, and the simplicity of the thermometer method, have caused the latter to become very commonly employed for determining the temperature rises in electrical machinery. The resistance method is then employed as a further refinement of, and a check upon, the use of a thermometer.

The temperature-rise in a dynamo depends upon a number of factors, such as the power converted into heat inside the machine, the armature speed, the ventilation. and the surface area of the coils; that is, upon the rate at which heat is generated and upon the facility with which that heat is dissipated.

To keep a constant check upon the temperature at which coils are working, in the case of large generators in important power stations, thermo-junctions (or electrical thermometers) are now inserted in machine windings and connected up permanently to indicating or recording instruments, so that the engineers running the plant can see what is going on without having to make special tests.

QUESTIONS

(See also Chapter X, Dynamos, and Chapter XI, d.c. Motors.)

1. Explain how magneto-generators act, and describe one of the following kinds: (*a*) Magneto for ignition in automobiles. (*b*) As used in ohmmeters. (*c*) As used for calling-up in telephone work.

2. How do you account for the great resistance experienced in rotating the armature of a dynamo supplying current ?

3. Enumerate the essential parts of a dynamo, writing them down in a table, and opposite each briefly explain the object and action of each part.

4. Define armature, brushes, rocker, field-magnet, pole-piece, commutator, spider.

5. Sketch and describe the action of a simple dynamo, having one coil of a complete turn for an armature.

6. Upon what does the e.m.f. generated by an armature depend ?

7. Sketch one type of F.M. for a four-pole, and one type for a multipolar machine, and indicate the path and direction of the magnetic flux by dotted lines and arrows.

8. Why are pole-cores sometimes laminated ? Describe various methods of fixing solid and laminated pole-cores to the frame.

9. Why are armatures provided with iron cores ? The iron cores of armatures in dynamos are generally made of a number of thin plates of iron, and not of one solid mass of iron, why is this ?

10. Define idle wire, core-plate, eddy current, salient pole, consequent pole, excitation of dynamos.

11. What is the effect of sinking the wire into a slot in the laminated iron core of a d.c. armature ? Give reasons for your answer.

12. What is meant by the terms "hysteresis loss" and "eddy current loss" in the iron cores of dynamo armatures ? How are the losses affected by the thickness of the plates ? In what magnetic and electrical qualities do the silicon-iron alloys, now often used for core-plates, differ from the ordinary iron generally used for the same purpose.

13. Mention the properties which are desired in the materials for insulating the wires in the armature slots of a continuous-current dynamo, and describe the tests which you would apply to ascertain if the materials had those properties.

14. Enumerate the different insulating materials required in the construction of a dynamo, and state where these are used. What are their mechanical and electrical properties ?

15. Draw sketches, showing the full details of the construction of the commutator of a dynamo. Describe the sources of trouble in some constructions, and how they have been overcome.

16. Show the usual method of insulating and securing the segments of a commutator. Explain the method of assembly.

17. Describe in detail how you would true up the commutator of a dynamo.

18. Explain as briefly as possible the advantages of a two-circuit over a multiple-circuit armature winding.

19. Distinguish between a simplex and multiplex armature winding.

20. Give a sketch, or sketches, to illustrate the winding of a drum armature for use in a four-pole field.

21. Classify dynamos, according to the mode of winding and connecting up the field-magnet circuits, and explain shortly their relative advantages.

22. Make a diagrammatic sketch of a shunt dynamo, showing the direction of rotation, polarity of magnets, and directions of currents in armature, field-magnets, and external circuits respectively.

23. Show by diagrammatic sketches the arrangement of field and armature winding in series, shunt, and compound-wound machines. Which would you install for (*a*) traction load, (*b*) arc-lamp lighting, and (*c*) charging accumulators, and why ?

24. Define magneto-machine, separately-excited dynamo, self-exciting dynamo, interpole dynamo.

25. Explain the process of putting a shunt dynamo into parallel with others already running, and of taking it out again without causing a flicker on the voltage, also how it takes its share of the load.

26. Explain fully the method of coupling up two shunt generators in parallel, and the modifications required if the two machines are compound-wound.

27. When a battery is charged from a shunt-wound dynamo driven by an oil engine, the ammeter needle fluctuates at every explosion, though the light of a lamp connected across it remains apparently steady. Explain this result.

28. Explain how a shunt dynamo builds up its field, and why it does so only to a certain point. On installing such a machine it fails to excite. Explain why it does so, and what steps you would take to correct it.

29. A continuous-current series generator is driven by a motor and connected to a resistance of 50 ohms. It fails to give any appreciable current. State the possible causes for this failure, and how you would overcome the difficulty.

30. What determines the voltage which a shunt-wound dynamo builds up to ? It is required to drive the armature of such a machine in the opposite direction. Explain what happens ; also any necessary alterations in the electrical connections.

31. Explain, with sketches, any necessary alterations in the wiring of a shunt dynamo if it is to be run in the opposite direction ; also, if it is to be used as a motor running, (*a*) in the same direction, (*b*) in the opposite direction.

32. Distinguish between series and shunt-wound dynamos. Explain what alterations in the electrical connections are necessary

to run them as motors, (*a*) in the same direction, (*b*) in the opposite direction.

33. On coupling two compound-wound dynamos in parallel to share a load it is found that one machine takes considerably more than the whole load. Explain this, and how it can be obviated.

34. Explain why it is dangerous to break the field circuit of a large shunt dynamo when running light. What precautions would you take if you wanted to separately excite the field circuit of the machine? How is the risk of breaking the field circuit of a shunt motor avoided in the ordinary starting switch?

35. Explain what is meant by cross-magnetization of armature and armature reaction. In what ways are these phenomena detrimental to the proper action of a dynamo.

36. What is meant by the "lead" in the brushes of a dynamo? Explain why sparking occurs at the brushes if the lead be wrong and no special means have been embodied in the design to prevent it.

37. Mention some of the causes of sparking in dynamos, and their remedies. Why is it that carbon brushes are now nearly always used?

38. Define pole-shoe, angle of lead, diameter of commutation, neutral points on a commutator.

39. Explain when and why it is necessary to move the brush position of a d.c. machine, and its effect upon the field excitation. What difference is there in the brush position of a generator and a motor when running (*a*) in the same direction, (*b*) in the opposite direction?

40. What is the effect of armature reaction upon the commutating properties of a dynamo? Also, explain the action produced by fitting interpoles to the machine, and show how they are connected in circuit.

41. A field coil of a dynamo has a resistance of 850 ohms at 20° C. After the dynamo has been run for several hours the resistance increases to 908 ohms. What is the average temperature of the coil under this condition? *Ans.* 37·06° C.

42. A shunt-excited generator when starting at room temperature shows a terminal pressure of 500 volts with a field current of 4 amps. After working for some hours the pressure has dropped to 480 volts, and the field current to 3·3 amps. What is the mean temperature rise of the field-coils? *Ans.* 40·9° C.

43. The pressure across the terminals of a field-winding is measured when (*a*) a current of 10 amps. is flowing and found to be 7·9 volts, and (*b*) when a current of 210 amps. is flowing and found to be 180 volts. What is the temperature of the windings when carrying the larger current? *Ans.* 21·25° C. higher than under conditions of (*a*).

44. The resistance of a d.c. armature, measured from opposite commutator sectors, is 0·013 ohm before running. After a 6-hours' run at full load the resistance is again measured and found to be 0·0147 ohm. What is the average temperature rise in the windings? *Ans.* 32·7° C.

NOTE.—In questions 41 to 44 take $a = 0{\cdot}004$.

APPENDIX

Books referred to in Vol. I for information which space prevents being given in the text of the respective Chapters.

Chap.	*Title.*	*Author.*	*Publisher.*	*Price.* s.	d.
I	C.G.S. System of Units . . .	Everett, J. D.	Macmillan	6	–
	Dictionary of Metric Measures . . .	Clark, L.	Spon	6	6
	Real Mathematics .	Beck, E. G.	Frowde	15	–
II	Power Factor Booklet	Electrical Apparatus Co., Ltd.		–	–
	Thermal Measurement of Energy .	Griffiths, E. N	Camb. Univ. Press	3	6
III	Electric Wiring, Fittings, Switches, and Lamps . . .	Maycock, W. P.	Pitman	10	6
	Alternating Current Bridge Methods .	Hague, B.	Pitman	30	–
V	First Book of Electricity and Magnetism	Maycock, W. P	Pitman	6	–
	Regulations for the Electrical Equipment of Buildings .	Inst.E.E.	Spon	1	–
	Electric Wiring Tables . . .	Maycock, W. P.	Pitman	5	–
	Regulations for Electricity in Factories	Home Office	King's Printers		6
VII	Measurement of Electrical Resistance .	Price, W. A.	Oxford Univ. Press	6	–
	Methods of Measuring Electrical Resistance	Northrup, E. F.	McGraw Hill	22	6
	Experiments with the Slide-wire Bridge .	Robertson D.	Crompton	3	–
VIII	Alternating Current Bridge Methods .	Hague, B.	Pitman	30	–
	Conductometer and Electrical Conductivity	Appleyard, R.	*Elec. Review*	3	–

Chap.	*Title.*	*Author.*	*Publisher.*	*Price.* s.	d.
	Electric Circuit Theory and Calculations . . .	Maycock. W. P.	Pitman	10	6
	Testing and Localizing Faults . .	Wright, J.	Constable	2	6
	Absolute Measurements in Electricity and Magnetism .	Gray, A.	Macmillan	42	–
	Electrical Instruments . . .	Murdoch & Oschwald	Pitman	12	6
	Electricity Supply Costs and Charges .	Sayers, H. M.	*Elec. Review*	3	–
IX	Practical D.C. Armature Winding . .	Wollison, L.	Pitman	7	6

GENERAL

	Industrial Electricity	Timbie, W. H.	Chapman & Hall	17	6
	Electrical Engineering	Hazeltine, L. A.	Macmillan	30	–

See also list at end of Vol. II

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The figures refer to the numbered paragraphs.