ELECTROMAGNETS AND WINDINGS

ELECTROMAGNETS AND WINDINGS

A Practical Treatise for the use of Engineers concerned with the Design and Operation of Electromagnetic Apparatus

By

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WITH 39 ILLUSTRATIONS
AND MANY USEFUL DESIGN TABLES

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PREFACE

THIS book is intended primarily for the use of engineers concerned with the design and operation of electromagnetic apparatus.

Particular attention is devoted to practical matters, and theoretical considerations have been reduced to the minimum required for the understanding of basic principles and the preparation of typical designs, of which several examples are given throughout the text.

It is hoped that the book may also prove useful to the student of electrical engineering, by indicating the way in which theoretical principles may be applied to the solution of problems arising in connection with the application of electromagnets.

G. WINDRED

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ELECTROMAGNETS AND WINDINGS

Chapter I

FUNDAMENTALS OF ELECTROMAGNETISM

IN this chapter we deal with those principles of electromagnetism which are essential for the design of practical electromagnets. The theory represented by these requirements is quite simple, although particular care is necessary in the matter of units, which are probably the greatest source of error in working out actual problems.

Terms and Definitions

The subject of electromagnetism embraces a rather wide range of terms and definitions, but comparatively few of these are sufficient for our present requirements. They are as follows:

Magnetic Flux may be defined as a measure of the total field consisting of imaginary lines of force produced by a magnetic body. It is thus equal to the density of the field multiplied by the area over which the field acts. The symbol is Φ, and the unit (one line of force) is called the Maxwell.

Flux Density, sometimes called the Induction, is a measure of the strength of concentration of flux, and is thus equal to the number of lines of force passing through unit area of field in a plane at right-angles to the direction of the flux. The symbol is B, and the unit (1 Maxwell or line of force per square centimetre) is the Gauss. It follows from the definition that $B = \Phi/A$, where A is the area through which the flux passes.

Magnetising Force is a measure of the magnetising action of a current flowing in a wire, and is equal to the magnetomotive force per unit length of the magnetic circuit acted upon by the wire. If T is the number of effective turns of wire passing round the magnetic circuit, and I the current in amperes which passes through the wire, then the magnetising force $H = 0{\cdot}4\pi TI/l$, where l is the length of the magnetic circuit in cms. The unit is called the Oersted.

Magnetomotive Force is the total magnetising force exerted on a magnetic body and is equal to Hl, where H is the magnetising force and l is the length of the magnetic circuit. The symbol is F, and the unit is the Gilbert. It follows from the definition of magnetising force that $F = 0{\cdot}4\pi TI$.

Permeability is the property of a magnetic substance which determines the flux density produced in it by a given magnetising force. The symbol is μ, and the unit has no name. From the definition it follows that $\mu = B/H$. In general, the permeability of a substance varies with the flux density. The reciprocal $1/\mu$ is called the specific reluctance or reluctivity.

Reluctance is a measure of the resistance to magnetisation of a magnetic circuit, and is given by $R = l/A\mu$, where l is the length of the magnetic circuit, A its area of cross-section at right-angles to the direction of the flux and μ the permeability of the substance comprising the magnetic circuit. The unit has no name. The reciprocal $1/R = A\mu/l$ is called the permeance. For air, $\mu = 1$ and the reluctance is therefore l/A, while the permeance is A/l.

THE MAGNETIC CIRCUIT

In calculating the properties of any magnetic circuit it is essential to have accurate knowledge of the properties of the material used;

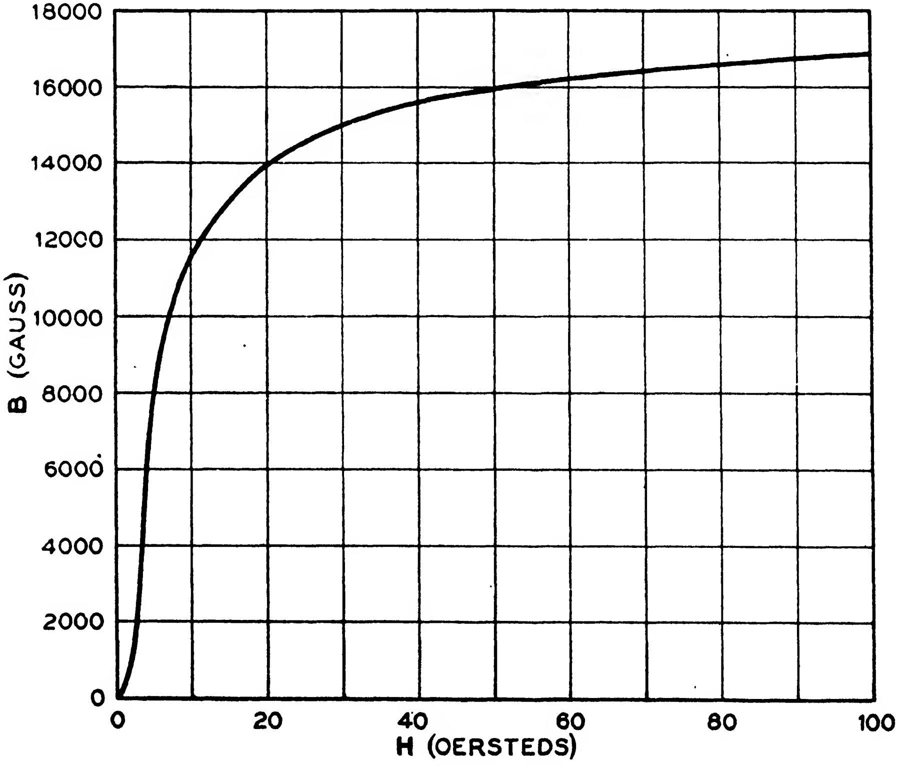

Fig. 1.—Typical b–h curve.

otherwise accuracy of calculation is a waste of effort. The magnetic properties of different classes of cast iron or steel may vary considerably, and when accurate results are required it is necessary to have the necessary data for the material used. The information is usually given in the form of the so-called B–H curve, as shown in Fig. 1, where the flux density B in gauss is plotted against H in oersteds (gilberts per cm.) for a sample of soft iron.

Particular importance attaches to the region of saturation in a B–H curve. This is the region where the curve departs from the almost linear commencing portion. In the case of Fig. 1 the region lies beyond about 10,000 gauss, and higher flux densities than this require a proportionately much greater magnetising force. It is consequently uneconomical to work at these high densities. On the other hand, there is no advantage in working at a very low density, since the amount of iron used is more than necessary. The shape of B–H curves for different grades of iron vary considerably, and it is never safe to assume that because a curve is available for cast iron, for example, that it will necessarily be appropriate for an untested cast iron sample.

It may be noted here that we are not obliged to use gauss and oersteds as units of B and H respectively. Since 1 sq. inch $= 2{\cdot}54^2$ sq. cm., the flux density B may equally well be expressed in lines per sq. inch, provided that we make

$$\text{lines/sq. inch} = 6{\cdot}45 \times \text{lines/sq. cm.}$$

Similarly, since the magnetising force in oersteds is reckoned per cm. length of the magnetic circuit, the value in inch units will be 2·54 times as great, that is, $0{\cdot}4\pi IT \times 2{\cdot}54 = 3{\cdot}19IT$. We have, therefore

$$\text{Ampere-turns per inch} = H \text{ (in oersteds)} \times 3{\cdot}19$$

With these equivalents we may plot B–H curves in lines per sq. inch against ampere-turns per inch, or alternatively provide both scales for B and H so that either may be used as desired, as in Fig. 5.

The relation between flux, magnetomotive force and reluctance in a magnetic circuit is similar to that of current, e.m.f. and resistance in an electrical circuit, as governed by Ohm's law. We have therefore

$$\text{Flux} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}} = \frac{0{\cdot}4\mu TI}{l/A\mu}$$

$$\text{or} \qquad \Phi = \frac{0{\cdot}4\pi TIA\mu}{l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

When the magnetic circuit consists of more than one material, so that the flux passes through them in sequence, the reluctances are added together, like resistances in series. In this case we have

$$\frac{0{\cdot}4\pi TI}{(l_1/A_1\mu_1 + l_2/A_2\mu_2 + \ldots.)} \quad . \quad . \quad . \quad . \quad (2)$$

where l_1, A_1, μ_1, etc., are the length, cross-sectional area and permeability of the successive paths.

High permeability is seen to be an essential for efficient working, and reasonable expense in obtaining good quality iron is usually repaid. Malleable cast iron, for example, has a higher permeability than ordinary cast iron, and several foundries now specialise in the production of high permeability iron castings.

A few examples will illustrate the principles outlined above. In the first case it is required to find the number of ampere-turns to produce a flux density of 3,000 gauss across an air gap 0·5 inch long. From formula (1) we have, since $\mu = 1$ for air :

$$\Phi = 0{\cdot}4\pi TIA/l, \text{ and } B = 0{\cdot}4\pi TI/l.$$

We must notice particularly that although our figure for B is in C.G.S. units, l is in inches and must accordingly be converted to cm. This gives us

$$\begin{aligned} TI &= Bl \times 2{\cdot}54/0{\cdot}4\pi \\ &= \frac{3000 \times 0{\cdot}50 \times 2{\cdot}54}{0{\cdot}4 \times 3{\cdot}14} = \frac{3810}{1{\cdot}256} = 3033 \textit{ ampere-turns.} \end{aligned}$$

Secondly, it is required to find the number of ampere-turns necessary to produce a flux of 25,000 maxwells across an air gap 0·25 inch long and 5 sq. inches cross-section. Here again we must notice that the units are mixed; the flux being in C.G.S. and the dimensions in inch units. Conversion is therefore necessary, A and l being multiplied by 6·45 ($= 2{\cdot}54^2$) and 2·54 respectively to convert to cm. We have

$$\Phi = 0{\cdot}4\pi TIA/l,$$

so that

$$\begin{aligned} TI &= l\Phi/0{\cdot}4\pi A \\ &= \frac{0{\cdot}25 \times 2{\cdot}54 \times 25{,}000}{0{\cdot}4 \times 3{\cdot}14 \times 5 \times 6{\cdot}45} = \frac{15{,}875}{40{\cdot}5} = 392 \textit{ ampere-turns.} \end{aligned}$$

As a final example, of a more involved type, we may consider the properties of an iron ring electromagnet of the material corresponding to the *B–H* curve in Fig. 1, the external and internal diameters being 9½ inches and 8 inches respectively, and the length 1 inch. The excitation is such that the magnetising force $H = 5$ oersteds, and from the data given it is required to find the reluctance of the magnetic circuit. We know that the reluctance is given by $l/A\mu$; also that $l = 8{\cdot}75\pi$ inches (8·75 inches being the mean diameter of the ring) and A, the cross-section of the ring is 0·75 sq. inch. If then we can find the value of the permeability μ, it will be possible to calculate the reluctance directly. By reference to the B–H curve we find that when $H = 5$ oersteds, $B = 8{,}500$ gauss, so that since $\mu = B/H$, we obtain $\mu = 1700$. It must not be overlooked that our units are again mixed; the dimensions of the ring being in inches, which means that l and A must be converted to cm. Making the necessary substitutions, the numerical value of the reluctance $l/A\mu$ will be

$$\frac{8{\cdot}75 \times 3{\cdot}14 \times 2{\cdot}54}{0{\cdot}75 \times 6{\cdot}45 \times 1700} = 0{\cdot}0083$$

It will be seen from these examples that considerable care must be exercised in the matter of units, and it is advisable to be as familiar as possible with conversions from English to Metric units and vice versa.

Magnetic Leakage

In the great majority of magnetic circuits a part of the total flux performs no useful function owing to the fact that it lies outside the region of usefulness. For example, a magnetic circuit containing an air gap will have its greatest concentration of flux through the region representing the shortest length of path (i.e., the lowest resistance), but outside this region there will be a relatively weak field, called the leakage field, which may contribute nothing to the purpose for which the field is used. In electrical machine design use is made of the so-called leakage coefficient, which is defined as follows:

$$\text{Leakage coefficient} = \frac{\text{total flux}}{\text{useful flux}} = \frac{\text{useful flux} + \text{leakage flux}}{\text{useful flux}}$$

The calculation of this coefficient is very complicated, except in the most straightforward cases, and although mathematical methods have been devised for estimating it in certain examples of electrical machine design, the practical design of electromagnets does not require these methods. However, the designer must always bear in mind the possibility of leakage fields and their effect on performance. The necessary allowances in design calculations are indicated in subsequent chapters.

The Effect of Joints

In many examples of practical design it is impossible to avoid joints in the magnetic circuit, and the question naturally arises as to what losses are introduced in this way. It is evident that a badly-made joint will represent an air gap, as well as a restriction of the cross-section, so that it must result in an increased reluctance and hence a reduced flux for a given excitation.

In some experiments carried out many years ago by J. A. Ewing, a wrought-iron bar 0·79 cm. in diameter was cut in the middle, and the faces carefully scraped to form a flat surface which was tested on a surface plate. Readings of B and H for the jointed bar were then compared with corresponding readings before cutting, and showed that the increase of reluctance due to the joint was equivalent to an air gap of 0·03 mm. It is probable that this increase is partly due to a reduction of permeability near the joint owing to the cutting process.

With regard to the effect of pressure, it was found, as would be expected, that the reluctance due to the joint became less as the pressure was increased. The effect of the joint was not entirely removed, however, until the pressure reached 226 kg. per sq. cm., representing nearly 1·5 tons per sq. inch. In the case of a smooth unscraped joint it was not found possible to remove its effect to any great extent even with very much higher pressures.

These results show the necessity for good joints, and it may be added that they should be designed not only so that they can be tightly clamped or bolted, but so that they do not represent a restriction of cross-section in the magnetic circuit; otherwise the reluctance of the circuit as a whole may be considerably increased.

THE A.C. MAGNETIC CIRCUIT

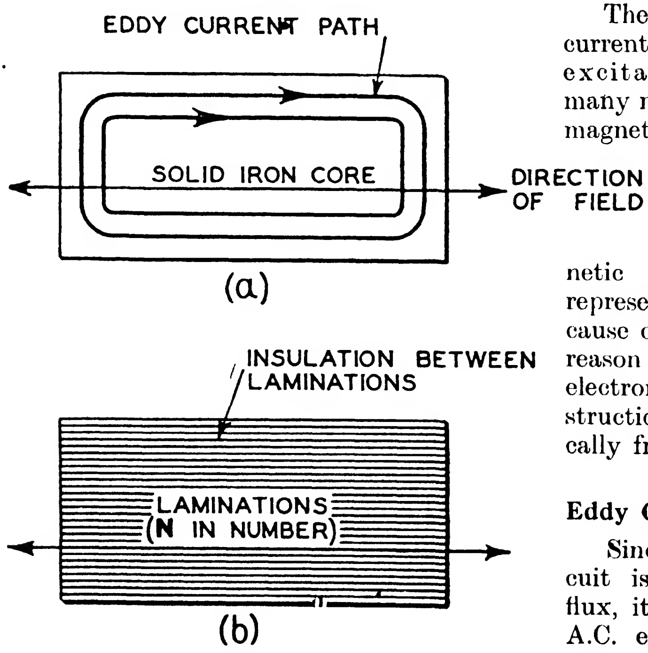

Fig. 2.—Solid and laminated cores in alternating field.

The use of alternating current as a means of excitation introduces many new effects into the magnetic circuit. One of these is the generation of eddy currents within the magnetic circuit itself and representing not only a cause of loss but also the reason why the A.C. electromagnet has a construction differing radically from the D.C. type.

Eddy Currents

Since a magnetic circuit is threaded by the flux, it follows that with A.C. excitation the flux generates circulating currents in the iron path.

If the core were solid, these so-called eddy currents would be high owing to the low resistance of their path and would cause considerable heating of the iron. No useful purpose is served by the eddy currents, which represent a source of loss and must be suppressed as much as possible in order to improve efficiency and reduce heating. In practice this object is achieved by building the iron circuit from laminations having their plane in the direction of the field as shown in Fig. 2. The laminations are only lightly insulated from each other owing to the very small voltages generated. Undue thickness of insulation reduces the effective amount of iron which can be accommodated in a given space.

Jointing of laminations should be avoided as far as possible, and if joints have to be made they should be interleaved in the manner shown in Fig. 3, in order to prevent an undue increase of reluctance. Tightness of joints is essential, as in the D.C. case, and clamping is preferable to bolting or riveting because it avoids reducing the effective cross-section of the iron.

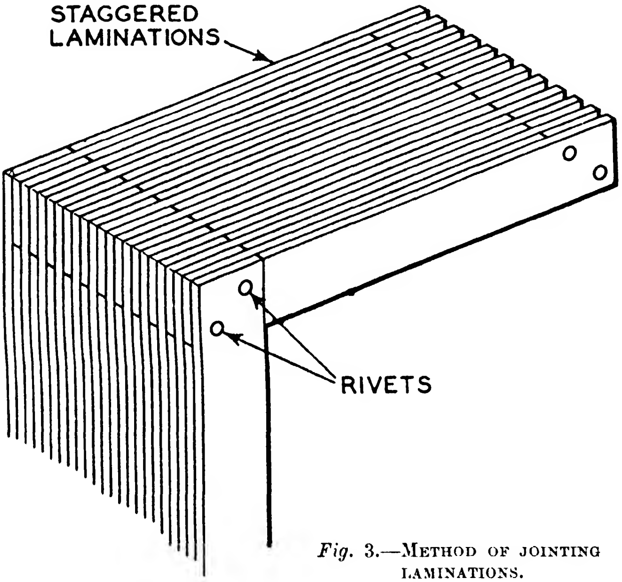

Fig. 3.—METHOD OF JOINTING LAMINATIONS.

The importance of the thickness of laminations used may easily be shown as follows. With reference to Fig. 2 (a), let E represent the small e.m.f. induced in the solid iron by the alternating field and R the resistance in the eddy current path. The corresponding wattage loss is E^2/R. In the case of the laminated circuit of Fig. 2 (b) however, the induced e.m.f. per lamination, which we call e, is now E/N, where N is the number of laminations, since the flux per lamination is $1/N$th of the total flux. Also, since the cross-section of each lamination is $1/N$th of the former value, the resistance r per lamination is N times R. In one stamping, the watt loss is given by

$$\begin{aligned} w &= e^2/r \\ &= \left(\frac{E}{N}\right)^2 \bigg/ NR \end{aligned}$$

$$= \frac{E^2}{N^3R} \quad . \quad . \quad . \quad . \quad . \quad . \quad .(3)$$

The total loss is evidently

$$Nw = E^2/N^2R,$$

from which it follows that the eddy current loss is proportional to the square of the thickness of the laminations. There are some obvious inaccuracies in the assumptions on which the foregoing simple theory is based, but the conclusion is quite accurate.

The magnitude of eddy currents can of course be reduced by employing laminations with a high electrical resistance. Sheet material with this property, but at the same time having the necessary degree of permeability, is available in a somewhat wide selection from different manufacturers. In the corresponding trade literature information is given concerning the *B–H* characteristics, specific resistance and eddy current loss at different frequencies, so that the best choice may be made for a given application by reconciling the general magnetic properties with eddy current losses and cost of material. Eddy current losses are usually expressed in watts per pound of the material at a given flux density and frequency.

Hysteresis

When a magnetic material is subjected to cyclic reversals of magnetisation, as in the case of A.C. electromagnets, energy is expended in the material owing to the lagging of the flux behind the impressed cyclic magnetising force. A typical curve showing the effect is given in Fig. 4, which applies to hard cast steel. Such a curve is called a hysteresis loop, and the loss of energy per unit weight or volume for a given sample of iron is proportional to the area of the corresponding loop.

If the iron is completely neutral, increase of magnetisation from the zero point will of course raise the flux density in accordance with the normal *B–H* curve of the material, as shown by the dotted line. At point *a* the direction of magnetisation is reversed, but instead of the flux density falling back along the dotted line it reduces only to the point *b* when $H = O$, and as *H* is increased in the negative direction, *B* is brought to zero at point *c*. As *H* is increased still further in the negative direction to the same value as the original positive swing, then reversed and carried through positive values once more, the complete hysteresis loop is traced out. The distance *Ob*, representing the flux density retained by the iron when *H* is reduced to zero is called the *retentivity*, while the distance *Oc*, representing the value of *H* required to reduce the flux density to zero is called the *coercive force.*

The amount of loss due to hysteresis for a given grade of iron varies with the frequency and the flux density, and is given approximately by Steinmetz's formula:

$$\text{Watt loss per cubic cm.} \doteq fkB^{1\cdot 6} \times 10^{-7},$$

where f is the frequency (cycles/sec.) and k the hysteresis constant, which has a value of about 0·003 for normal iron sheet. In practice it is customary to express the hysteresis loss in watts per pound, and it may therefore be added to the eddy current loss so as to give what is known as the total loss for the material. A low hysteresis loss is obtained by alloying silicon with steel, as in the wide range of "silicon-steels" now available. Representative data are given in Table I.

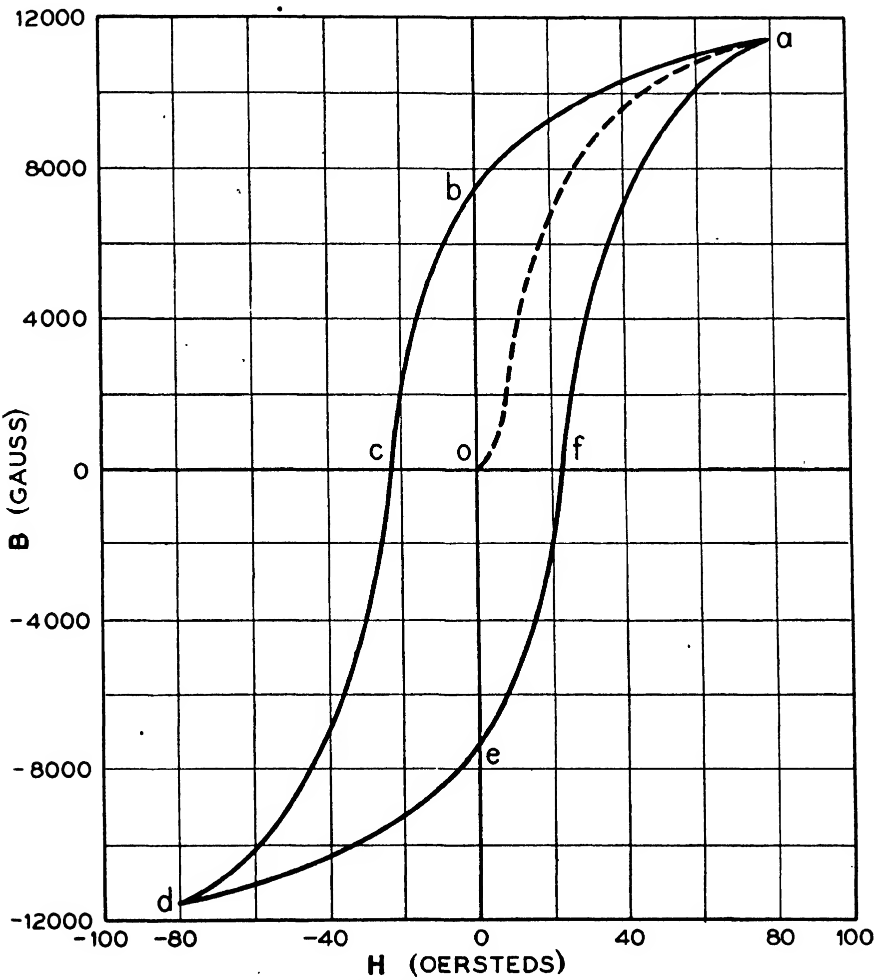

Fig. 4.—TYPICAL HYSTERESIS LOOP FOR HARD CAST STEEL.

NOTES ON MAGNETIC MATERIALS

There are many varieties of iron and steel from which to select in the design of electromagnets, and the choice of a suitable material is often difficult. In addition to general suitability from the magnetic standpoint,

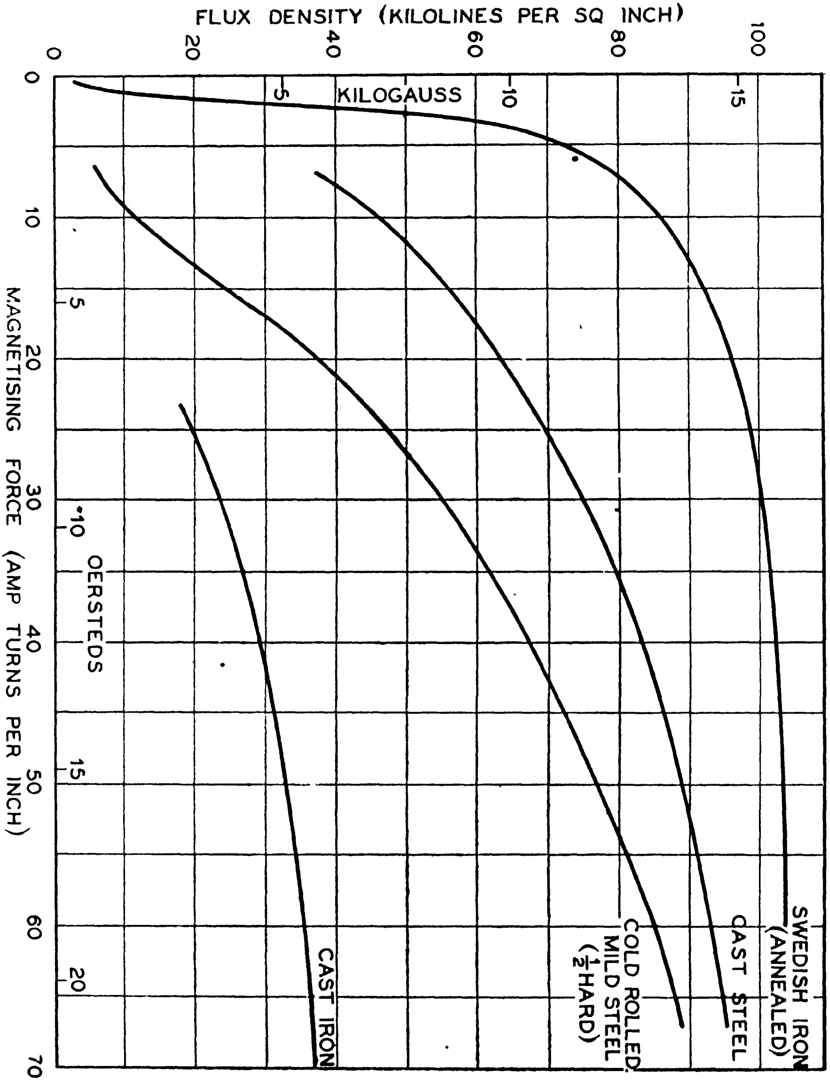

Fig. 5.—MAGNETISATION CURVES FOR REPRESENTATIVE MATERIALS.
The four curves show the B/H relation for Swedish Iron, Cast Steel, Cold Rolled Mild Steel and Cast Iron respectively. The values of H are given in oersteds and also as ampere turns per inch.

such questions as availability and cost must also be considered, and sometimes the choice is influenced by the type of construction. General particulars of the principal materials suitable for electromagnets are given below, and typical data are given in Fig. 5.

Soft Iron

This form of iron is very pure and has a high permeability and low coercive force; the latter factor being of importance in quick-releasing relays, for example. Annealing under carefully controlled conditions is necessary to obtain the best magnetic characteristics. This material is one of the best for general applications, provided that use can be made of bar or plate, as these are the usual forms. Swedish charcoal iron belongs to this class, and has similar magnetic properties.

Cast Iron

The magnetic properties of this material are somewhat indifferent. The permeability and saturation flux density are low, and the coercive force high. Magnetic circuits of cast iron are therefore relatively bulky, and are justified chiefly on account of cheapness and the ease of casting and machining. The properties of different samples vary considerably, are are greatly modified by annealing.

Malleable Cast Iron

This material has magnetic properties decidedly superior to those of ordinary cast iron; the best results being obtained by annealing of the castings. The mechanical and machining properties are similar to those of cast iron, but the cost is higher. When castings of this material are available, the higher cost is justified in most cases owing to the superior magnetic properties and consequent economy in material.

Cast Steel

A good magnetic grade of cast steel has magnetic properties about intermediate between those of the best grades of soft iron and ordinary cast iron. These properties vary considerably according to variations in composition and heat treatment. A typical application of cast steel is the body of a large lifting magnet, where good magnetic properties are required in combination with mechanical strength. Fairly intricate castings may be produced without difficulty.

Cold Rolled Steel

This material is usually available in sheet and strip form up to about $\frac{1}{4}$ inch thickness, and is useful in the construction of relays, contactors and similar devices where the magnetic circuit may be formed from the material. There are several degrees of hardness, ranging from the dead soft, which is comparable magnetically with soft iron, to the hard variety, which has rather inferior magnetic properties and is liable to crack in bending.

Sheet Materials

There is now a wide range of sheet materials having extremely varied properties, each suited to some limited range of applications. Not all of these sheets are applicable for electromagnets, since in some cases the saturation densities are much too low.

Silicon steel is characterised by low losses on A.C., and is widely used for A.C. electromagnets, for which purpose a medium grade with a silicon content of about 2 per cent is usually satisfactory. The total core loss decreases with increasing proportions of silicon.

Nickel iron is characterised by a high permeability, but rather low saturation point; about the same as annealed cast iron (100,000 lines/sq. inch). The losses are very low. Its use in electromagnets is practically confined to the cores of special relays, where high permeability is required for high sensitivity, coupled with low coercive force.

TABLE I

TOTAL WATT LOSS PER POUND AT 50 CYCLES FOR SILICON STEELS

$B = 10{,}000$ gauss (64,500 lines/sq. inch)

Grade.	*Silicon* %	*Resis.* $\frac{\mu\Omega}{cm^3}$	*Thickness of Sheet (inches)*						
			0·014	0·016	0·018	0·020	0·022	0·025	0·030
Lohys	0·2	14	1·32	1·41	1·51	1·62	1·74	1·95	2·38
Special Lohys ...	0·75	20	1·09	1·15	1·23	1·33	1·45	1·63	2·00
Medium Resistance	1·5	30	1·00	1·05	1·09	1·14	1·20	1·29	1·45
42 Quality ...	2·5	40	0·88	0·92	0·97	1·02	1·07	1·14	1·25
41 Quality ...	3·0	45	0·75	0·78	0·81	0·84	0·90	0·97	1·09
48 Quality ...	3·5	50	0·69	0·73	0·77	0·81			
Stalloy	4·0	55	0·63	0·67	0·70	0·74	0·77	0·82	0·90
Special Stalloy ...	4·0	55	0·59	0·62	0·65	—	—	—	—
Extra Special Stalloy	4·2	55	0·54	0·57	0·60	—	—	—	—
Super Stalloy ...	4·3	58	0·49	—	—	—	—	—	—

Courtesy of Joseph Sankey & Sons, Ltd.

Chapter II

TRACTIVE ELECTROMAGNETS

THE various forms of electromagnet used in practice may be broadly classified under three main headings, as follows:

1. Tractive type, in which an armature of some kind is attracted by an electromagnet.
2. Holding or lifting type, also sometimes called portative, in which the poles of the electromagnet are brought into contact with magnetic material for the purpose of lifting or other movement.
3. Solenoid or plunger type, in which a sliding core or plunger is drawn into a solenoid.

In the present chapter we are concerned only with the first two types, which rely upon similar principles of design and operation. Solenoid electromagnets are dealt with in Chapter III.

Examples in the first category are to be found in electromagnetic contactors and relays of the type in which a hinged, pivoted or floating armature is attracted by an electromagnet when the exciting coil is energised. An outstanding example in the second category is the lifting magnet used for handling magnetic materials and thus dispensing with the necessity for auxiliary lifting apparatus such as hooks or slings.

General Principles of Design

In the design of electromagnets of any kind it is necessary to give consideration to several factors, and it is not always possible to control these factors independently. For example, it is frequently necessary in practice to employ an existing magnet core in a given case, regardless of whether or not a more efficient design could be made for the particular conditions. In other cases, but more rarely, it is possible to develop an individual design.

Another factor is represented by the quality of the iron to be used in the electromagnet. The permeability in most cases is known only approximately, and since it has a very marked effect upon operation, the best that can be expected is an approximation to the performance expected on the basis of an assumed value of permeability.

Magnetic leakage represents a further factor which has great influence upon performance, but is very difficult to assess with any degree of accuracy. It is always necessary to make allowances for this effect, but the allowance is of necessity approximate.

Finally, it must be remembered that there are discrepancies, great or small, between design and practice in the case of the windings. A further allowance is necessary here also, to allow for variations from the expected number of turns and value of resistance.

From this enumeration of possible discrepancies it will be realised that the art of electromagnetic design involves judicious estimates of likely deviations in practice from calculated values. Experience in the design and subsequent testing of different types of electromagnet is of the greatest value in this connection.

The Magnetic Circuit

We have already seen that for any magnetic circuit the flux is given by

$$\Phi = 0{\cdot}4\pi TIA\mu/l, \qquad . \quad . \quad . \quad . \quad . \quad (4)$$

so that, since $B = \Phi/A$,

$$B = 0{\cdot}4\pi TI\mu/l \qquad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

In the case of air, $\mu = 1$, and the flux density is accordingly expressed by

$$B = 0{\cdot}4\pi TI/l, \qquad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

so that for air gaps the number of ampere-turns required to produce a given flux density depends only upon the length of the air gap.

Considerable care is necessary in the matter of units. If B is expressed in gauss (i.e., lines per sq. *cm.*),

$$\text{Ampere-turns per } cm. \text{ (air)} = B/1{\cdot}257$$

and

$$\text{Ampere-turns per } inch \text{ (air)} \doteqdot 2{\cdot}54\, B/1{\cdot}257 = 2B \text{(approx)}.$$

If B is expressed in lines per sq. *inch*,

$$\text{Ampere-turns per } inch \text{ (air)} = 2B_{in}/6{\cdot}45 = 0{\cdot}31B_{in}.$$

In this case it is advisable to use a modified symbol such as B_{in} to indicate the units in which the flux density is expressed.

Magnetic Pull

The mechanical pull between the parallel faces of area A on either side of an air gap completing a magnetic circuit is given by Maxwell's formula

$$P = B^2A/8\pi \qquad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

If B is expressed in gauss and A in sq. cm., then P is in dynes. It should be specially noted that this formula holds goods only in the case of parallel surfaces over which B is constant. In practice this implies that the formula is valid only for small air gaps unless the necessary allowances are made for the flux leakage and distortion due to long gaps.

Since 1 pound = 4·448 × 10^5 dynes, the pull in pounds when B is in gauss (and A in sq. cm.) is given by

$$P = \frac{B^2A \times 2{\cdot}54^2}{8\pi \times 4{\cdot}448 \times 10^5} = \frac{B^2A}{1{\cdot}73 \times 10^6} \text{ (approx.)} \quad . \quad . \qquad (8)$$

If, however, B is expressed in lines per sq. inch, then

$$P = \frac{B_{in}{}^2A}{6{\cdot}45^2 \times 1{\cdot}73 \times 10^6} = \frac{B_{in}{}^2A}{72 \times 10^6} \textit{ pounds} \text{ (approx.)} \quad . \qquad (9)$$

From these formulæ it will be found, for example, that the pull produced by a flux density of 20,000 gauss (or 129,000 lines per sq. inch) is 231 pounds per sq. inch. Since the pull is proportional to the square of the flux density, it falls off rapidly as the flux density is reduced.

It follows that magnetic leakage plays a very important part in designs involving the calculation of magnetic pull, since a leakage of only 10 per cent will reduce the pull by nearly 20 per cent. A widening of the air gap also causes a considerable reduction in flux density, so that the pull falls off rapidly as the air gap is increased.

With reference to equation (7) it may be pointed out that an increase of pole area, although increasing the value of A, represents a reduction of B (assuming that the excitation remains fixed), and since the pull is proportional to B^2 the result is a reduction of pull. Conversely, if A is made small, B becomes large and the pull is increased. For this reason we have the rather curious fact that the force required to separate the left-hand side of the armature in Fig. 6 from its pole-piece is considerably greater than that corresponding to the right-hand side.

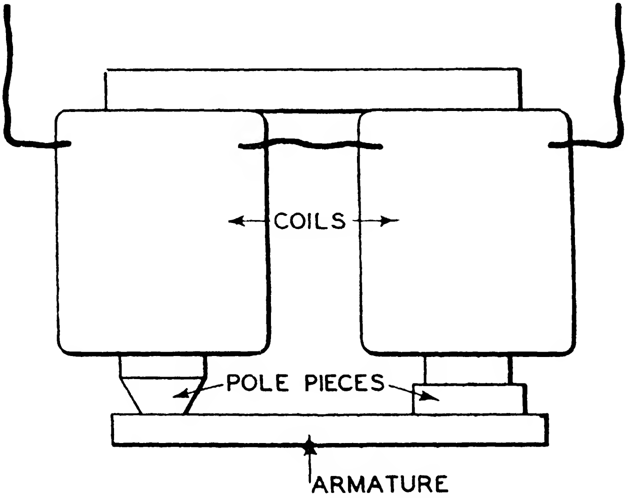

Fig. 6.—Electromagnet with alternative types of pole-piece.

Tractive Electromagnets

The tractive type of electromagnet usually has the form shown in Fig. 7. In this case the core consists of two cylindrical limbs attached by means of screws to a cross-piece. The screw holes should not be unduly large, so as to take away too much metal from the core, but this factor is not so important if steel screws are used, so as to replace the magnetic material. The pole-pieces should sit squarely on the cross-piece, so as to avoid air gaps and consequent flux distortion. Soft iron or mild steel should be used for all magnetic parts, including the armature. The best magnetic qualities naturally give the best results.

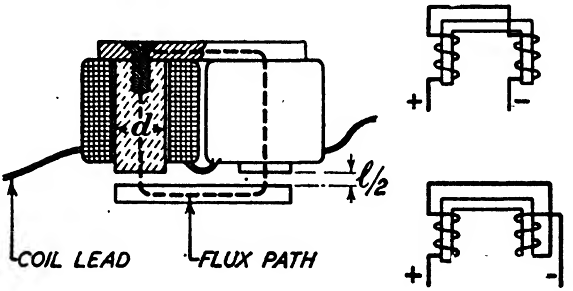

Fig. 7.—ARRANGEMENT OF TRACTIVE TYPE ELECTROMAGNET.

It should be remembered that an excessively large and heavy armature is undesirable, since its weight detracts from the useful pull which can be developed for a given excitation of the windings. The cross-section of the armature should be a minimum consistent with the flux density it has to carry, and should in no case exceed the cross-section of the poles or cross-piece.

An important point with this type of electromagnet is that the air gap between the poles and the armature, as indicated in Fig. 7, should be small. If the gap is large, the leakage becomes excessive and the available pull is very much reduced. For this reason the tractive type electromagnet is suitable only for operating with a short stroke.

The windings are connected so that the flux path is as shown dotted in Fig. 7. This requires that the respective poles should have alternate polarity, so that the connections will be in accordance with one or other diagram in Fig. 7, according to whether the coils are wound in the same or in opposite directions.

We have already seen that, with inch units of measurement, ampere-turns per inch of air gap $= 0{\cdot}31B_{in}$. If l is the length of gap, we have therefore

$$TI/l = 0{\cdot}31B_{in}, \text{ and } B_{in} = TI/0{\cdot}31l.$$

Reverting now to equation (9) we see that

$$P = B_{in}^2 A/72 \times 10^6 \text{ pounds.} \quad . \quad . \quad . \quad (10)$$

so that by substitution we have

$$P = A(TI)^2/(0{\cdot}31l)^2 72 \times 10^6 = A\left(\frac{TI}{2660l}\right)^2 \text{ pounds.} \quad . \quad . \quad . \quad (11)$$

This convenient formula may be rearranged as follows in order to express the number of ampere-turns required to produce a given pull:

$$TI = 2660l\sqrt{\frac{P}{A}} \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Owing to leakage and the fact that this formula does not include the ampere-turns required by the iron circuit, the number of ampere-turns calculated in this way must be suitably augmented to cover both factors. An increase of 25 per cent is usually sufficient to allow for leakage in cases where the gap is small in relation to the pole area, while an increase of 10 per cent is usually sufficient to cover the ampere-turns required by the iron. It is, of course, in all cases desirable to make such factors as liberal as possible, so as to ensure that the magnet will perform the intended work.

Application of Formulæ

One or two examples will help to show how the formulæ are applied. If we assume that the electromagnet shown in Fig. 7 has a pole area of 0·30 sq. inch., and that a pull of $\frac{1}{4}$ lb. is required at a distance of $\frac{1}{8}$ inch, the necessary excitation in ampere-turns may be found from equation (12).

We have

$$\begin{aligned} l &= 2 \times \tfrac{1}{8} = 0{\cdot}25. \\ P &= 0{\cdot}25. \\ A &= 2 \times 0{\cdot}30 = 0{\cdot}60. \end{aligned}$$

By subsitution,

$$\text{Ampere-turns} = 2660 \times 0{\cdot}25\sqrt{\frac{0{\cdot}25}{0{\cdot}60}} = 429.$$

To allow for leakage, this figure must be increased by a factor of 25 per cent, so that

$$\text{Total ampere-turns} = 1{\cdot}25 \times 429 = 536.$$

The allowance for the iron circuit may be taken as 10 per cent, giving $1{\cdot}1 \times 536 = 590$ for the final value of ampere-turns.

As an alternative proposition, it may be desired to determine the amount of pull which can be obtained from a given electromagnet with a known excitation, calculated from knowledge of the winding particulars. Suppose, for example, it is known that each of the coils has 200 turns and a resistance of 45 ohms, and that the two coils are used in series on a 60-volt supply. The total number of ampere-turns will be given by

$$TI = 400 \times \frac{60}{90} = 266$$

In calculating the pull, we must make a suitable allowance for leakage, and reduce this figure by about 25 per cent, so as to give approximately 200 ampere-turns for use in the formula.

If we consider the case of the same magnet as in the foregoing example, where l (total) = 0·25 and A (total) = 0·60, then from equation (11) the pull will be

$$P \text{ (pounds)} = 0{\cdot}6\left(\frac{200}{665}\right)^2 = 0{\cdot}054 \text{ lb.}$$

or 0·76 oz.

With a shorter stroke, say $\frac{1}{16}$ in., the pull will be increased to

$$P \text{ (pounds)} = 0{\cdot}6\left(\frac{200}{332}\right)^2 = 0{\cdot}216 \text{ lb.}$$

or 3·5 oz.

The procedure in designing from first principles an electromagnet of the type shown in Fig. 7 to perform a given duty is illustrated in the following example. It is assumed that we wish to design an electromagnet with an armature capable of pulling 100 lb. through ¼ inch. The values of flux density in air gap and iron may be taken as 30,000 and 80,000 lines per sq. inch respectively for a high quality iron, thus working the iron just below the knee of the excitation curve and avoiding the large number of ampere-turns for higher densities (see Fig. 5).

Since from equation (9) the pull in pounds per sq. inch is given by $B_{in}^2/72 \times 10^6$, the value for $B_{in} = 30{,}000$ will be 12·5 pounds per sq. inch, so that the area of *each* pole face will require to be 50/12·5 = 4 sq. inches. The corresponding diameter pole (d in Fig. 7) will be 2¼ inches (approx.), and the useful flux per pole is 4 × 30,000 = 120,000 lines, so that the cross-section of iron in the armature will require to be 120,000/80,000 = 1·5 sq. inches. If the width is made equal to the pole diameter the thickness will be 1·5/2·25 = 0·66, or ⅝ inch approx.

We have already seen that for air, ampere-turns per inch = $0{\cdot}31B_{in}$, so that the ampere-turns required for the two gaps are 0·31 × 30,000 × 0·25 × 2 = 4650. This means that with an addition of 10 per cent to cover the ampere-turns required by the iron circuit we shall require 2558 ampere-turns per coil. This figure must be regarded as an absolute minimum. With regard to pole dimensions, it is usual to make the length about four times the diameter, but this depends to some extent upon the space required by the winding, which in turn is governed by the service conditions, i.e., whether the magnet is required to be energised for long or short periods. Questions of coil design are dealt with in Chapter IV.

Special Cases

Problems concerning tractive electromagnets do not always resolve themselves into a design for lifting a given weight vertically through a specified distance. In the case of contactors and relays, for example, the pull is often exerted horizontally, and in the case of resilient contacts the load varies considerably during the travel of the armature. This will be understood from consideration of the design shown in Fig. 8, representing a contactor or relay of conventional design with a pivoted armature carrying a spring-loaded contact. During the initial part of the armature movement the pull required is only the amount necessary to overcome the weight of the armature (and the opposing torque of any pivot springs which may be used) and the friction due to the pivot. As the closing movement progresses, however, the contacts eventually touch, and from this point onwards the electromagnet must produce sufficient pull to overcome the increasing load due to compression of the contact spring. In some designs requiring high contact pressure this load is very high. The closing of such contactors is of course facilitated by the fact that as the air gap becomes smaller the flux increases, so that the pull increases rapidly as the armature closes. Closure is also helped to some extent by the inertia of the armature during the portion of the travel before the contacts touch, but in every case the design must allow for the heavy load represented by the contact pressure.

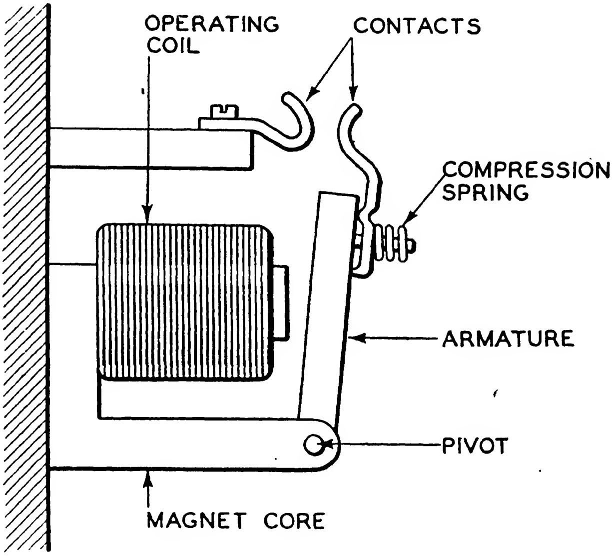

Fig. 8.—ARRANGEMENT OF CONVENTIONAL CONTACTOR OR RELAY.

Holding or Lifting Electromagnets

It is possible to use a horse-shoe type electromagnet of the form shown in Fig. 7 for lifting magnetic materials, but the usual design is the so-called mushroom type as shown in Fig. 9. This design is widely used in practice for lifting and transporting all kinds of magnetic materials, ranging from shavings and turnings to heavy steel bars, plates, rods and tubes. It will be seen that the mushroom type of construction can be readily made weatherproof and robust; both features being necessary when the magnet is used in exposed places and under heavy conditions of service.

It is not possible to predict with great accuracy the maximum load which may be lifted by a magnet of the type shown in Fig. 9, as this will depend upon the shape of the load lifted, its magnetic properties and also the nature of the contact established between magnet and load. Theory can provide a guide in this connection, but large factors of safety must be allowed in the calculations. The performance of a given magnet also depends upon the rating, i.e., whether the windings are designed for continuous or intermittent use. In the former case, the watts dissipated in the winding will of course be smaller, and the load less. A magnet which is switched on only for short periods can absorb a much greater wattage and therefore carry a much heavier load than one of the same size designed for longer periods. The majority of lifting magnets have intermittently rated coils, and owing to the massive construction it is possible to allow a large number of watts without overheating.

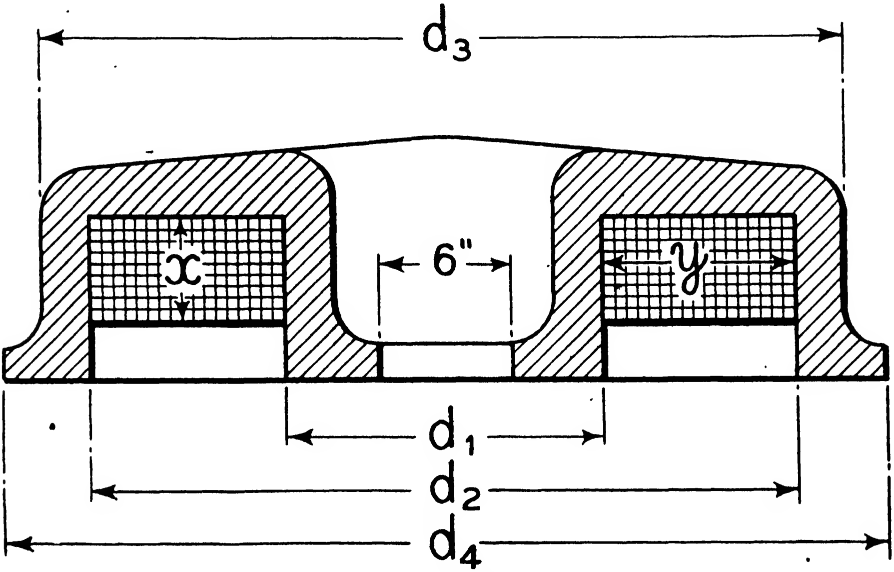

Fig. 9.—CROSS-SECTION OF CIRCULAR LIFTING MAGNET.

The pull developed by an electromagnet in contact with a magnetic body is given by Maxwell's formula, as expressed in equation (7). The pull is independent of the gap in the region of contact, provided that the flux density is uniform, so that if the value of B is known or can be calculated it is possible to estimate from equation (7) the force of attraction. If, for example, an electromagnet of the form shown in Fig. 7 has a pole area of 10 sq. cm. per pole and the flux density is 18,000 gauss, the pull per unit area at each pole in C.G.S. units will be

$$\begin{aligned} P &= B^2/8\pi \\ &= 18{,}000^2/25{\cdot}13 \doteq 1{\cdot}29 \times 10^7 \textit{ dynes per sq. cm.} \end{aligned}$$

The total pull per pole will thus be

$$10 \times 1{\cdot}29 \times 10^7 = 1{\cdot}29 \times 10^8 \textit{ dynes},$$

so that the total pull is,

$$2{\cdot}58 \times 10^8 \textit{ dynes}$$

or $$2{\cdot}58 \times 10^8/981 = 263 \textit{ kilograms.}$$

Design of Lifting Magnet

A tentative design for a lifting magnet may be carried out on the following general lines. It is assumed that the magnet is to lift a piece of iron or steel weighing 10 tons, and that there is an air gap of 0·1 inch between the magnet face and the surface of the load, which is assumed to be flat. The magnet takes the form shown in Fig. 9.

A good value for the flux density in the air gap is $B_{in} = 50{,}000$. The necessary area *per pole* can be calculated from equation (9), giving

$$\begin{aligned} A &= 72 \times 10^6 \times 11200/B_{in}{}^2 \\ &= \frac{72 \times 10^6 \times 11200}{50{,}000^2} = 323 \textit{ square inches.} \end{aligned}$$

For the ampere-turns required to produce this flux density in the air gap (see page 22), we have for the two gaps

$$\begin{aligned} TI &= 2 \times 0{\cdot}1 \times 0{\cdot}31 \times \mathrm{B}_{in} \\ &= 3100 \textit{ ampere-turns.} \end{aligned}$$

As an approximation, we may assume that the m.m.f. required for the iron circuit is one-tenth of that required for the gaps, so that for the total excitation we obtain

$$1{\cdot}1 \times 3100 = 3410 \textit{ ampere-turns.}$$

On the assumption of a 6-inch diameter hole in the centre of the magnet body, we can see from Fig. 9 that

$$A = \frac{\pi}{4}(d_1^2 - 6^2)$$

and therefore $$d_1 = 21 \textit{ inches} \text{ (approx.)}$$

The outer pole face dimensions will depend upon the space required by the coil, and hence upon the type of duty for which the magnet is intended. It can be shown (see page 72) that the winding section ($x \times y$ in Fig. 9) is equal to

$$IT/iz,$$

where i is the current density in the wire and z the space factor. Reasonable coil proportions are such that $y = 2x$, so that

$$2x^2 = IT/iz$$

and

$$x = \sqrt{IT/2iz}$$

If, as is usually the case, the space factor is in the region of 0·5, we have simply $x = \sqrt{IT/i}$. In the present case, $IT = 3410$, so that if we assume a current density of 1500 amperes per sq. inch in the magnet wire we have

$$x = \sqrt{3410/1500} = 1\tfrac{9}{16} \textit{ inches} \text{ (approx.)}.$$

From this we find that d_2, the overall coil diameter, will be

$$d_1 + 2y = 21 + 6\tfrac{1}{4} = 27\tfrac{1}{4} \textit{ inches} \text{ (approx.)}.$$

The thickness of the iron shell of the magnet may now be determined as follows. We will assume that the leakage factor is 25 per cent, which means that the total flux per pole in the iron will be 1·25 times that in the air gap and will thus be given by

$$\Phi = 1{\cdot}25 B_{in} A = 1{\cdot}25 \times 50{,}000 \times 323$$

Taking a value of $B = 80{,}000$ for the iron circuit, the cross-section of iron path required will be $\Phi/80{,}000$, and from Fig. 9 it is seen that this must be equal to $\frac{1}{4}\pi(d_3^2 - d_2^2)$. If A_1 is the required section of iron, we have accordingly

$$\begin{aligned} d_3 &= \sqrt{\frac{4A_1}{\pi} + d_2^2} \\ &= \sqrt{\frac{4 \times 1{\cdot}25 \times 50{,}000 \times 323}{3{\cdot}142 \times 80{,}000} + 27{\cdot}25^2} \\ &= 32\tfrac{1}{2} \textit{ inches} \text{ (approx.)} \end{aligned}$$

This means that the shell of the magnet will be $2\frac{5}{8}$ inch thick. An additional lip will be required, for bolting on the plates which retain the coil, and if we allow $1\frac{3}{4}$ inch for this lip, the overall diameter (d_4) of the magnet will be 36 inches.

The principal dimensions determined in this way form a basis for the final magnet design from the mechanical standpoint. Clearance must obviously be allowed between the end of the coil and the bottom surface of the magnet so that adequate insulation and coil retainers may be incorporated. The inner parts of the body must also be of sufficient section for mechanical strength, and the necessary attachments included for the use of a three-point chain suspension.

It should be particularly noted that several designs of a lifting magnet can be made for the same work by employing different values of flux density in the gap. High values will require less iron, so that the casting will be cheaper, but the coil will be more expensive owing to the greater excitation and consequently greater amount of copper required. It is a good plan to work out a few tentative designs, making estimates of the cost of iron and copper for each, and then to select the most economical design. It must also be borne in mind that the *total* weight of a lifting magnet is also important, since it has to be carried by the crane in addition to the normal load.

Rectangular Lifting Magnets

In some cases it is more convenient for the magnet to be of rectangular instead of circular form. Two or more rectangular magnets may be grouped on a spreader bar, for example, for the lifting of long bars, tubes or sheets. The design of such magnets is in every way similar to the example just given; the calculations being simply modified to suit a rectangular coil and magnet body.

Lifting Magnets as Extractors

Magnets of either shape may be used for extracting magnetic objects from materials carried on a conveyor belt, for example. In this case the magnet is suspended as closely as possible above the material, so that maximum effort is exerted on any magnetic pieces as they pass underneath. From time to time the accumulation of such pieces on the face of the magnet must be removed.

When a lifting magnet is used for work of this kind it usually requires to be left in circuit continuously, which is not the case in ordinary lifting applications. Care must be taken to ensure that a safe value of coil heating is not exceeded.

Special Considerations

Two important factors must constantly be borne in mind in all electromagnet design. They are respectively the effects of line voltage variation and the heating of the winding itself.

It is well known that supply voltages are merely nominal, and that variations above and below this nominal figure are inevitable under ordinary conditions of working. It is evident that the desired performance of an electromagnet can be ensured at all times only if its winding is designed for the lowest supply voltage encountered under normal working conditions. For this reason it is good practice when designing an electromagnet to base the coil design on a voltage 10 per cent lower than the nominal value.

With regard to the heating of the winding, the effect is naturally to increase the resistance, with the result that the current and therefore the excitation are reduced. Since the pull is proportional to the square of the flux density this action has a pronounced effect upon performance, and must be taken into consideration in coil design. We may consider, for example, the effect produced in a copper winding by a temperature rise of 50°C. The resistance at this temperature is given by

$$R = R_c (1 + kt)$$

where R_c is the resistance at normal room temperature, k the temperature coefficient of resistance for copper (0·004 in the °C. scale) and t the temperature rise. The formula shows that for 50°C. rise the resistance rises 20 per cent, so that with a constant terminal voltage the ampere-turns are reduced by nearly 17 per cent and the electromagnet pull by nearly 31 per cent. For this reason, the estimated number of ampere-turns should always be increased by a factor of about 25 per cent.

Chapter III

SOLENOID ELECTROMAGNETS

IN its simplest form, the solenoid type electromagnet consists of a cylindrical coil in which an iron plunger is free to slide. The arrangement is normally used in an upright position, as shown at (*a*) in Fig. 10, so that when the coil winding is energised the plunger is drawn upwards in the direction of the arrow. The pull exerted on the plunger depends upon its position inside the coil. If the top of the plunger is flush with the bottom of the coil, the pull is small, owing to the weakness of the magnetic field near the coil ends, and is found experimentally to amount to only about 10 per cent of the maximum pull developed when the plunger is farther in. As the plunger moves into the coil, the pull increases rapidly to its maximum, owing to the fact that the flux is augmented by the presence of an appreciable amount of iron in the magnetic circuit.

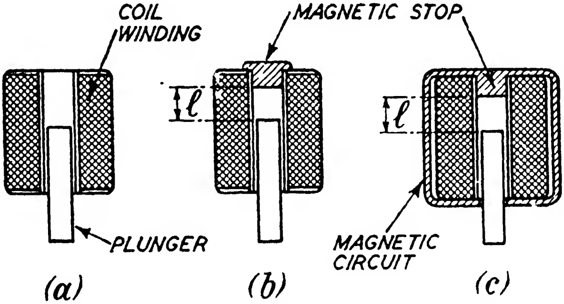

Fig. 10.—ALTERNATIVE FORMS OF SOLENOID.

The maximum pull is exerted when between 40 per cent and 80 per cent of the plunger length is inside the coil. After this the pull falls rapidly, becoming zero when the plunger is in its position of rest. If the lengths of coil and plunger are equal, this position will be when the ends are flush.

If the plunger is longer than the coil, it will come to rest with approximately equal projections from the coil at both ends. This simple arrangement is not used to any extent in practice, since the pull obtainable is small in relation to the size of the coil in consequence of the low permeability of the magnetic circuit and the high percentage of leakage.

The way in which the pull varies with the position of the plunger in a simple solenoid is shown in Fig. 11. The actual amount of pull depends of course upon the number of ampere-turns in the coil. In a long solenoid, the total work depends upon the ampere-turns per unit length, and is not otherwise dependent upon the length. For example, a solenoid 6 inches long will give the same pull as one 9 inches long if 50 per cent more ampere-turns are used. It may be noted, however, that in the case of a long solenoid, a given amount of wire produces more turns owing to the smaller mean diameter. In general practice the coil proportions are usually such that the coil diameter is about three times that of the plunger.

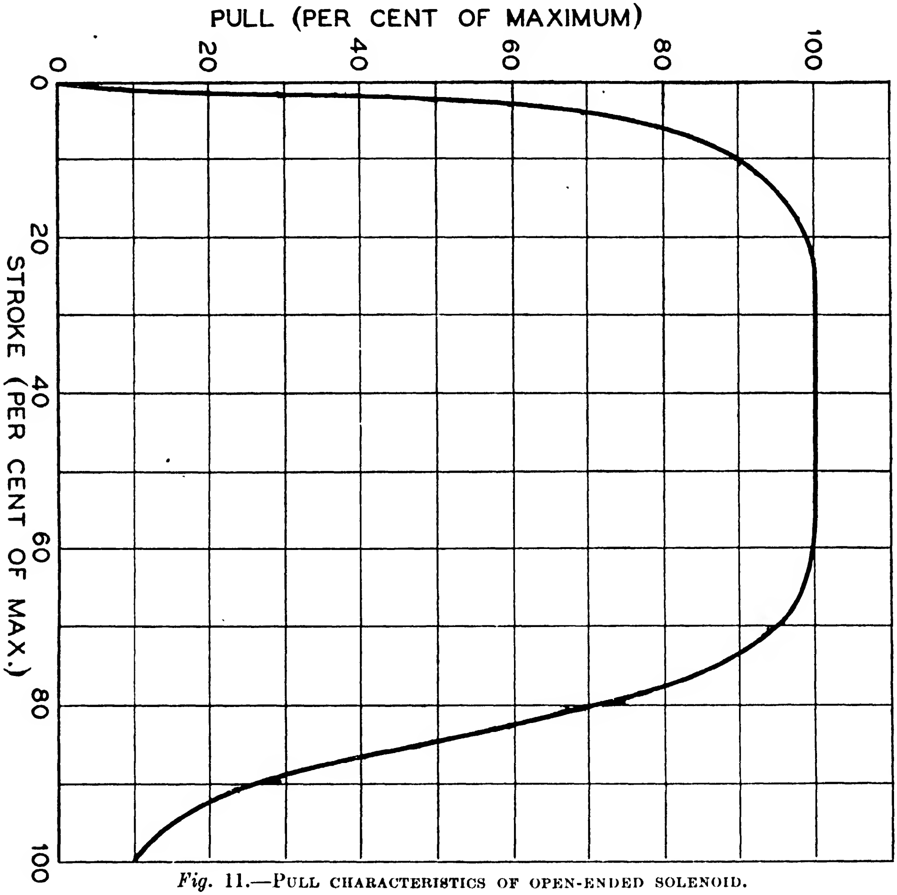

Fig. 11.—Pull characteristics of open-ended solenoid.

The pull exerted near the end of the travel of the plunger may be greatly increased by means of an iron stop fitted in the top of the coil as shown in Fig. 10 (*b*). This stop has little or no effect upon the pull at a long stroke, since it does not appreciably augment the flux under these conditions. When the top of the plunger approaches the stop, so that the air gap is very short, the pull is greatly augmented by the attraction of the stop.

Theoretically, the best position for the bottom end of the stop is about the centre of the coil, where the flux is a maximum, but in practice it is placed in the upper part of the coil so that the stroke of the plunger is not unduly restricted.

The best arrangement, and the one generally adopted in practice, employs a complete magnetic return path for the flux produced by the coil and also incorporates the end stop, as shown in Fig. 10 (*c*). The reduced reluctance of the magnetic path results in a considerable increase of flux and a consequent increase of pull. The pull may be regarded as having two components: one due to the solenoid effect, which we will denote by P_s, and the other due to the pull of the magnetic stop, which we will call P_m.

Considering first P_s, it will be evident that its magnitude with a given coil excitation (ampere-turns) will be inversely proportional to the length of the coil, since the shorter the coil, the more intense the solenoidal field. The magnitude of P_s is directly proportional to the number of ampere-turns produced by the coil and to the cross-sectional area of the plunger.

The formula is accordingly

$$P_s = \frac{kTIA}{L} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where A is the cross-sectional area of the plunger and L is the length of the coil. The value of the constant k depends upon the proportions of the electromagnet, the degree of magnetisation of the iron and the units in which A and L are expressed. The values of k determined by experiment for solenoids of normal design vary between the approximate limits of 0·0096 and 0·0057 when A and L are in inch units. It is safer to use the latter factor in order to ensure adequate pull.

With regard to the pull P_m due to the stop, this will be as given by equation (11) of Chapter II, in which A will be the cross-sectional area of the stop, presumed to be the same as that of the plunger, and l will be the air gap between plunger and stop. It is seen that P_m is inversely proportional to the square of l, so that the pull due to the attraction of the stop increases rapidly as the gap becomes shorter, i.e., towards the end of the stroke.

This action of the stop is shown by the curves in Fig. 12, representing the results obtained with progressively longer stops (*a*), (*b*), (*c*).

Calculation of Pull

The total pull of the solenoid is given by

$$P = P_s + P_m$$

so that from equations (11) and (13) we have

$$P = \frac{0{\cdot}0057\, TIA}{L} + A\left(\frac{TI}{2660l}\right)^2$$

$$\text{or} \qquad P = ATI\left(\frac{1}{175L} + \frac{TI}{2660^2\, l^2}\right) \qquad . \quad . \quad . \ (14)$$

This formula permits the calculation of the approximate pull of a given solenoid of the ironclad type with a coil giving a known number of ampere-turns excitation. In practice it is always advisable to assume that the full number of ampere-turns is not effective, so as to cover the effects of leakage and other inevitable deviations between calculation and actual performance. When a new design is developed it is excellent practice to compare the performance with the results anticipated on the basis of equation (14), so as to determine by what percentage the calculated number of ampere-turns should be reduced to agree with the actual measurements. In most cases, a reduction of 25 per cent is sufficient.

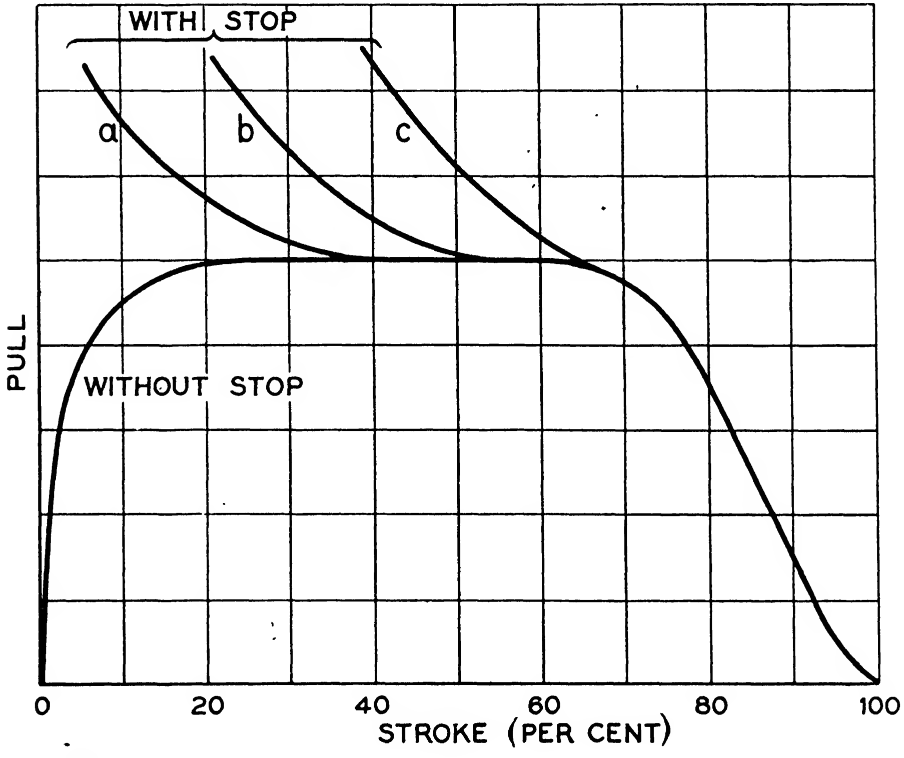

Fig. 12.—PULL CHARACTERISTICS OF SOLENOID WITH AND WITHOUT END STOPS.

In order to avoid the labour of working out equation (14) in every case, the values of P_s and P_m may be plotted against ampere-turns for various values of L and l respectively. If desired, the correction for effective ampere-turns may be allowed for in the curves, so that for finding the pull in a given case all that is necessary is to find P_s and P_m from the curves relating to the appropriate values of L and l and take the sum of the respective pulls to represent the total pull of the solenoid.

As an example, we may take the case of a solenoid having a coil $2\frac{1}{2}$ inches long and with a plunger cross-section of $\frac{3}{4}$ sq. inch. If the calculated number of ampere-turns produced by the coil is 2,500, the pull developed in relation to the stroke can be calculated from equation (14). At $\frac{1}{2}$ inch stroke, we have

$$\begin{aligned} P &= 0{\cdot}75 \times 1875 \frac{1}{175 \times 2{\cdot}5} + \left(\frac{1875}{2660^2 \times \frac{1}{4}}\right) \\ &= 1406\,(0{\cdot}0023 + 0{\cdot}00106) \\ &= 4{\cdot}7 \text{ lb. approximately.} \end{aligned}$$

It will be noticed that in the formula a 25 per cent reduction of calculated ampere-turns has been allowed, giving a figure of 1875 for IT.

If it is desired to find the number of ampere-turns necessary to produce a certain pull with a solenoid of known dimensions, use can be made of the curves already mentioned, giving values of P_s and P_m per sq. inch of plunger in relation to ampere-turns for different values of L and l. The limit to the pull available is fixed by coil heating for a given type of winding, and when the number of ampere-turns has been decided upon it is necessary to work out the winding details, as shown in Chapter IV and V, so as to ensure that the heating will not be excessive.

A given solenoid is capable of producing more pull when energised for short periods than when used continuously, since a greater wattage may be dissipated in the coil, and it follows that different coils may be designed according to whether the duty is continuous or intermittent.

Design of Ironclad Solenoid

It is evident that the completion of the magnetic circuit of a solenoid by means of an iron frame will appreciably increase the flux and pull for short air gaps, but with long gaps this advantage is lost owing to the small effect of the iron on the total reluctance under these conditions. When the air gap is small in relation to the pole area the magnetic leakage at normal flux densities is small. This is consequently the most efficient arrangement, and should be adopted wherever possible, especially in the case of large solenoids. Where this condition is fulfilled it is permissible, and perhaps more conservative, to base the design on the pull due to the stop only and neglect the solenoidal pull.

We know from Maxwell's formula that the pull depends upon B^2A, so that it is possible to produce a wide variety of designs for performing the same duty. A large value of A, i.e. a large plunger, requires less flux density and therefore less ampere-turns, but the iron circuit is bulky. Alternatively, a small plunger requires more flux density and ampere-turns, so that more copper is required in the winding. From the economic point of view, the best design is that which gives the required performance with the minimum total cost, but this factor is not always of basic importance. It will be realised that a great deal depends upon the magnetic quality of the iron used, and with a high-grade magnet steel the ampere-turns for a given flux density may be less than a third of the number required for cast iron.

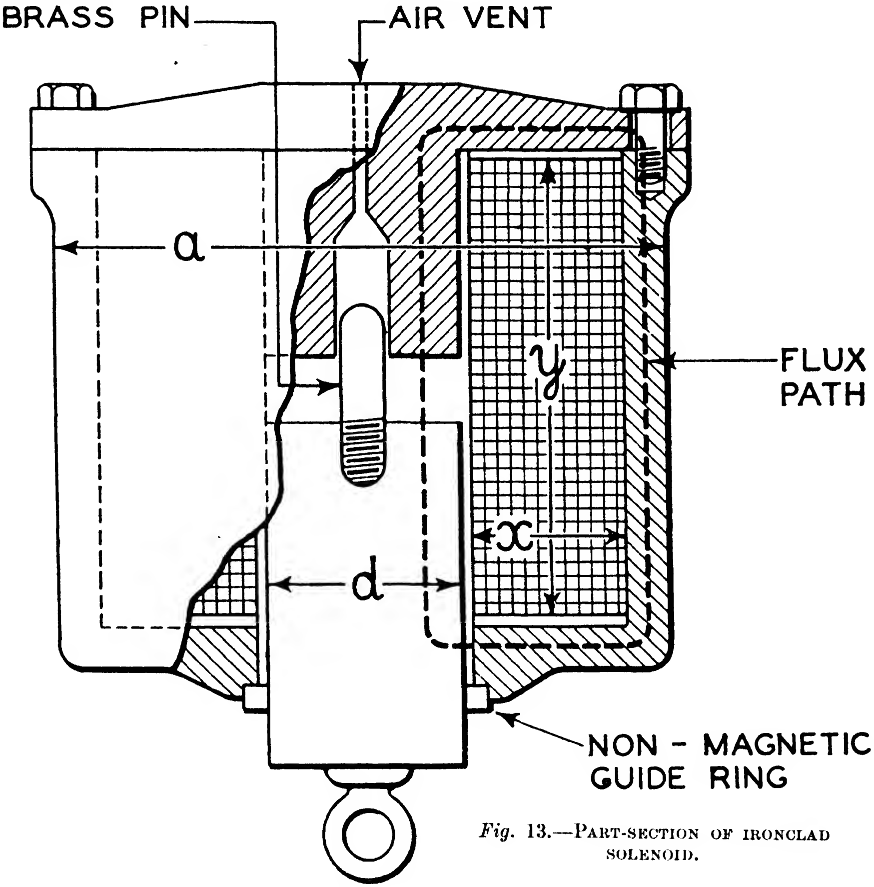

Fig. 13.—Part-section of ironclad solenoid.

As a practical example of design, we may consider the case of a solenoid of ironclad construction as shown in Fig. 13 to exert a pull of 100 pounds through one inch stroke. From equation (9) of Chapter II we know that the pull in pounds per sq. inch is given by $B_{in}^2/72 \times 10^6$. If we assume a flux density of 40,000 in the mild steel plunger and stop the pull is then

$$40{,}000^2/72 \times 10^6 = 40^2/72 = 22{\cdot}2 \text{ lb./sq. inch.}$$

so that if d is the diameter of the plunger and stop we must have

$$A = \tfrac{1}{4}\pi d^2 = 100/22{\cdot}2 = 4{\cdot}5$$

and therefore $d = \sqrt{4{\cdot}5/\tfrac{1}{4}\pi} = 2{\cdot}4$ inches (approx.)

Neglecting the ampere-turns required by the iron circuit, which may be estimated later, the number required by the gap (see page 22) is

$$0{\cdot}31B_{in} = 0{\cdot}31 \times 40{,}000 = 12{,}400 \text{ ampere-turns.}$$

This figure must be regarded as an absolute minimum; it does not allow for possible discrepancies in the quality of the iron, or for flux leakage, or for the loss of excitation due to the normal coil heating, and should be increased by a factor of about 25 per cent to cover these factors. A figure of 15,000 ampere-turns is a safer estimate.

The outside dimensions of the solenoid are of course determined by the size of the coil, i.e. upon whether it is intended for intermittent or continuous duty, and to a lesser extent upon the supply voltage on which it is intended to operate. If we assume that the solenoid is to be energised for only short periods, we may allow a current density as high as 2000 amperes per sq. inch in the winding, so that from the relationships given on page 72 we find that with a winding space factor of 0·5 the winding section $x \times y = IT/iz = 15{,}000/2000 \times 0{\cdot}5 = 15$ sq. inches. A winding deeper than 3 inches is not satisfactory from the viewpoint of heating, so that taking $x = 2{\cdot}5$ inches we get $y = 6$ inches. This establishes the general proportions of the solenoid.

Ordinary cast iron may be used for the shell, but in this case B must be much lower, say 20,000. Since the total flux $\Phi = BA = 40{,}000 \times \tfrac{1}{4}\pi d^2 = 40{,}000 \times 4{\cdot}5 = 180{,}000$, then neglecting leakage we find that the cross-sectional area of the shell has to be $\Phi/B = 180{,}000/20{,}000 = 9$ sq. inches.

The size over the coil, allowing for insulation and clearance, is seen to be about 8 inches, so that if a is the external diameter of the shell we must have

$$\tfrac{1}{4}\pi(a^2 - 8^2) = 9$$

Thus a is found to be approximately 8·7 inches, or say 8·75 inches, which gives a figure of $\tfrac{3}{8}$ inch for the thickness of the cast iron shell.

The throat at the lower end of the solenoid, through which the plunger passes, represents a further air gap, and the ampere-turns required to overcome it are reduced by making the throat long, so as to reduce the flux density in the gap. If the throat is 1 inch long, for example, the area across which the flux passes will be approximately $2{\cdot}5\pi$ sq. inches, and the flux density will be $180{,}000/2{\cdot}5\pi$. It follows that for a clearance of $\tfrac{1}{32}$ inch (0·031 inch) between throat and plunger the ampere-turns will be given by

$$\frac{0{\cdot}31 \times 180{,}000 \times 0{\cdot}031}{2{\cdot}5 \times \pi} = 220 \text{ approx.}$$

This number may be added to the total (15,000) already found, but the proportion required for the throat only becomes appreciable for large clearances and short lengths of throat.

Similarly, the relatively small number of ampere-turns required for the iron circuit can be estimated from magnetisation curves of the kind shown in Fig. 5 giving the ampere-turns per inch required by cast iron and mild steel for the appropriate values of B. In the present example the length of the iron circuit is seen to be of the order of 20 inches.

If the magnetic joint where the top part of the solenoid fits on to the shell is accurately machined and tightly bolted there will be no necessity to make further increase in the number of ampere-turns required.

If a solenoid of the type under consideration a point arises in connection with the cushioning effect of the air above the plunger when the solenoid operates. A vent may be provided as shown in Fig. 13 to prevent excessive slowing of the motion of the plunger by this action, and in some cases an adjustable valve is fitted at the top so that a condition is obtained where the action is not unduly slow and at the same time the shock caused by sudden striking of the stop is reduced. A typical ironclad solenoid is shown in Fig. 14.

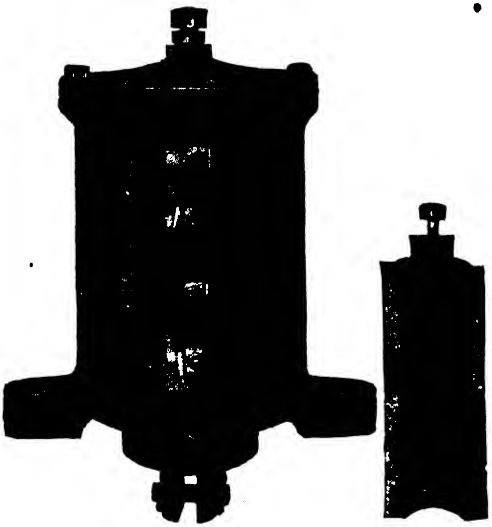

Fig. 14.—TYPICAL IRONCLAD SOLENOID. (*Metropolitan-Vickers*)

The Cone Plunger

The maximum work produced by a solenoid, as represented by the product of pull and stroke, occurs at a definite stroke, and this particular stroke is obviously the most efficient one. In the case of an ordinary ironclad solenoid, the maximum work is developed at a short stroke, which is not often a convenient one for the particular application. The difficulty may be overcome by the use of a lever arrangement, but this introduces complication, reduced efficiency owing to frictional losses in the moving parts, and a reduction of resultant pull owing to the increased weight to be lifted by the plunger.

Maximum work at a longer stroke can be obtained by the use of a cone plunger engaging with a conical recess in the stop as shown in Fig. 15.

With this arrangement the work is the same, but the pull less and the stroke greater than in the case of the flat-ended plunger. It has been found that good results are obtained with a 60° cone and recess. With this angle the stroke is equal to twice the magnetic gap, as shown in Fig. 15.

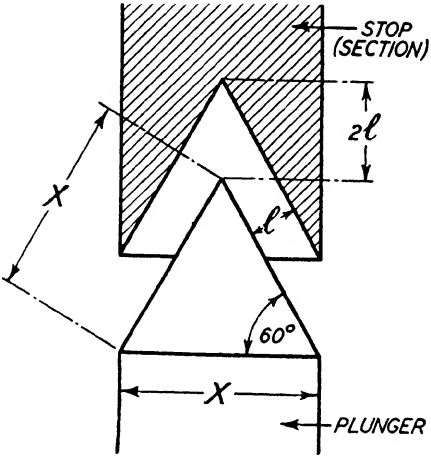

Fig. 15.—CONE PLUNGER FOR D.C. SOLENOID.

In order to obtain the same flux with a given coil excitation, the reluctance of the magnetic circuit must be the same as in the flat-ended plunger. With a 60° cone, the attracting surface area is given by $A = \frac{1}{2}\pi X^2$ (conical surface of 60° cone) whereas for the flat plunger $A = \frac{1}{4}\pi X^2$ (X = plunger diameter). This means that, for the same reluctance, l will have to be doubled in the case of the cone plunger, since

$$\text{Reluctance} = l/A\mu$$

where μ is the permeability. The magnetic gap l is measured perpendicular to the face of the cone, and in the case of the 60 degree cone amounts to one-half of the stroke. It follows that for the same work the stroke of the cone plunger is four times that of the flat plunger.

We have seen that the pull of the end stop is given by

$$P_m = A\left(\frac{TI}{2660l}\right)^2$$

With the 60° cone plunger, both A and l are doubled, so that P_m, measured perpendicular to the cone surface, is one-half the value for the flat plunger and the pull in the direction of travel is one-quarter. Since, as we have seen, the stroke of the cone plunger is four times, it follows that the same amount of work (pull × stroke) should be done in both cases. In actual tests the work of the coned plunger solenoid is usually somewhat greater.

The maximum work, representing the most efficient operation, consequently occurs with a longer stroke, and in many cases this feature allows direct operation of the load without the introduction of lever mechanism. The foregoing calculations do not allow for discrepancies due to magnetic leakage and deformation of the flux in the air gap caused by the conical surfaces. For this reason, the conclusions arrived at must be regarded as approximations which explain the advantage of the cone plunger rather than allowing exact calculation of its performance. The characteristics of flat and coned plunger solenoids are shown by the curves in Fig. 16.

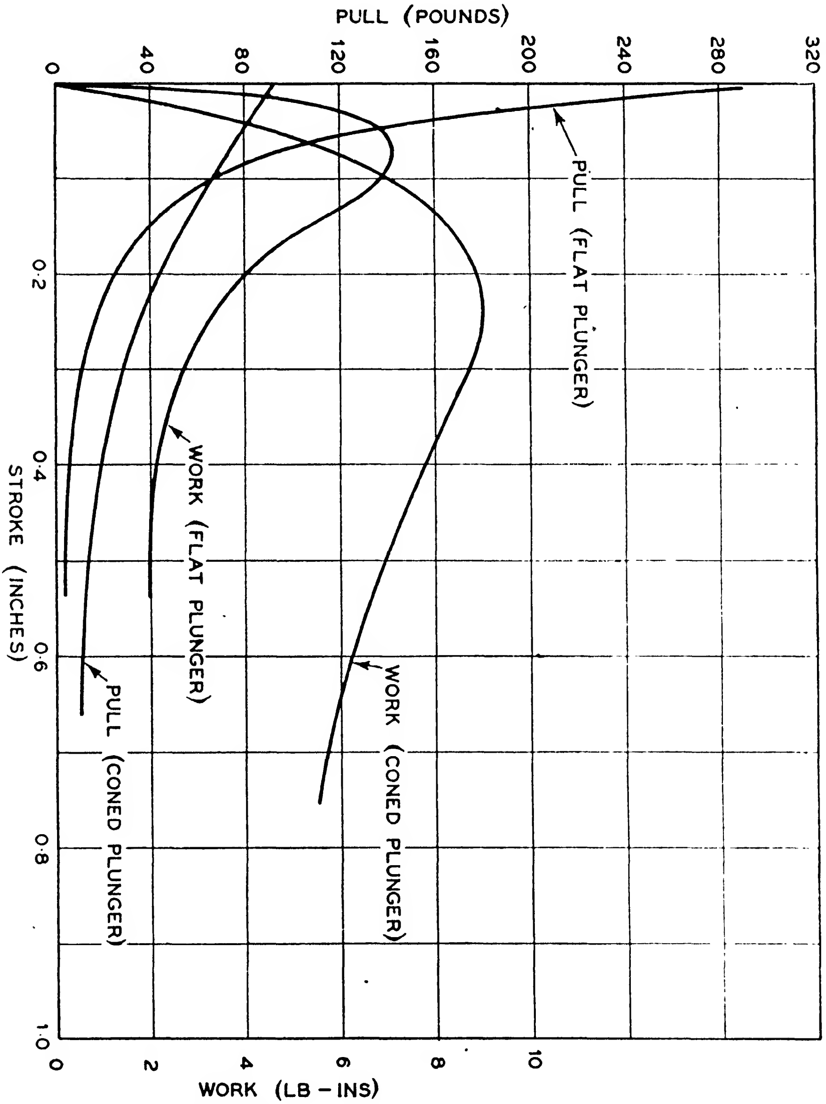

Fig. 16.—CHARACTERISTICS OF SOLENOID WITH FLAT AND CONED PLUNGERS.

A.C. SOLENOIDS

The use of electromagnets on alternating current is limited in practice almost exclusively to the solenoid type, which has a wide range of application and is manufactured in a variety of sizes, according to the pull and stroke required. Except in the case of very small solenoids for intermittent service and absorbing only low power, the use of alternating current necessitates the iron circuit being laminated, and this feature causes a radical difference in design between D.C. and A.C. solenoids. Owing to the complication introduced by lamination of the magnetic circuit, A.C. solenoids are generally more bulky and expensive than similar D.C. solenoids.

A given flux density in an A.C. solenoid will produce about half the pull as in a D.C. solenoid of the same proportions. It must be noticed, however, that the ampere-turns are no longer dependent upon the number of turns and the resistance of the coil winding, but upon the number of turns and the impedance: a factor which depends upon the inductance of the winding as well as its resistance and the frequency of the A.C. supply.

The effect of the impedance is to reduce the current on a given voltage to only a fraction of what it would be with the same D.C. voltage. Coil windings for A.C. solenoids are characterised by relatively few turns of wire and a low resistance in comparison with D.C. coils.

In the A.C. case the ampere-turns are given by

$$TI = \frac{ET}{\sqrt{R^2 + (\omega L)^2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

where the expression under the root sign is the impedance of the coil, comprising the following factors—

R = resistance of coil;
ω = $2\pi f$, where f is the frequency of the A.C. supply;
L = inductance of coil.

The three variables T, R and L are thus seen to determine the ampere-turns produced by a coil when connected to an alternating current supply of voltage E and frequency f. We know how to estimate the value of R, and can measure it readily in any given coil, but the inductance L is a very different proposition. It may be predicted theoretically between rather wide limits, but the equations are complicated. In any case the value of the inductance depends upon the nature of the magnetic circuit on which the coil is used, as well as the amount of current flowing in the coil.

In practice, the performance of A.C. coils is usually determined on the basis of data obtained from other similar coils on similar magnetic circuits. When new windings have to be determined without previous data of this kind it is customary to make up experimental coils from which the necessary information can be obtained. It may be noted here that in many cases the coil impedance is very largely reactive, which means that R in the impedance equation may be neglected in relation to the reactance ωL. Equation (15) then reduces to

$$IT = TE/\omega L \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

If now we assume that L remains constant for a coil with a fixed number of turns, it is seen that there is a direct relationship between the voltage and frequency on which a given coil may be used. If it is known, for example, that a certain coil operates satisfactorily on a voltage E and frequency f, then in order to obtain the same ampere-turns upon a voltage $2E$, the value of ωL for the coil must be twice its original value. Since L is constant, $\omega = 2\pi f$ must be twice as great as before, and since 2π is constant this means that the frequency will require to be doubled. It follows from this that a given coil which operates satisfactorily on a 220-volt, 25-cycle supply, for example, will also be suitable for a 440-volt, 50-cycle supply. It must be remembered that this is only a general rule, and may not apply in some cases.

A most important factor in A.C. coil design is provision against the short-circuiting of turns in the winding, either during the winding process or under operating conditions. A certain amount of vibration is present in the case of A.C. windings, owing to the pulsations caused by the reversals of current and flux at the supply frequency. This tends to cause friction between the turns of the winding and may lead to internal short circuits.

This occurrence is a very serious one, since the short-circuited part of the winding acts as the closed secondary of a transformer and is thus the seat of a high induced current. This gives rise to local overheating in the coil, which is conducive to further breakdown. It frequently happens that the whole winding is ruined in this way. It follows that in the case of A.C. windings it is particularly necessary for the wire to have adequate insulation and for the whole winding to be effectively impregnated, so as to prevent relative movement of the respective turns, in addition to preventing the ingress of moisture, which is a primary consideration for both A.C. and D.C. coils.

Inrush Current, or Kick Current

The reactance of an A.C. solenoid coil varies with the position of the plunger. With a large gap, i.e. at long stroke, the inductance L is small and the current high. As the plunger moves into the coil, the inductance increases and the current accordingly falls. The current at the moment of switching on, with a large air gap, is sometimes called the inrush current, or kick current, and may amount to more than ten times the current corresponding to the fully operated, or sealed, position. The ampere-turns at the early part of the stroke are consequently high, and the pull is correspondingly augmented. The maximum work in the case of the A.C.

solenoid usually occurs at maximum stroke. This is a very useful feature, since it dispenses with the necessity for lever mechanism.

The heating effect of the high initial current is not important unless the solenoid is switched on frequently, since the time taken by the plunger in completing its stroke is normally only a fraction of a second. It will be understood, however, that if this motion is delayed the high current will persist for a correspondingly long time and thus have an appreciable heating effect, since the heating of the winding is proportional to the square of the current.

In an A.C. solenoid, the iron circuit is also the seat of a temperature-rise, owing to the effects of hysteresis and eddy currents. The heating is reduced by using laminations for the parts comprising the magnetic circuit, and the magnetic qualities of the laminations used have an important effect upon the solenoid performance as well as the heating. In so far as the iron itself is concerned, there is no objection to a temperature as high as 80°C., but it must be borne in mind that a proportion of

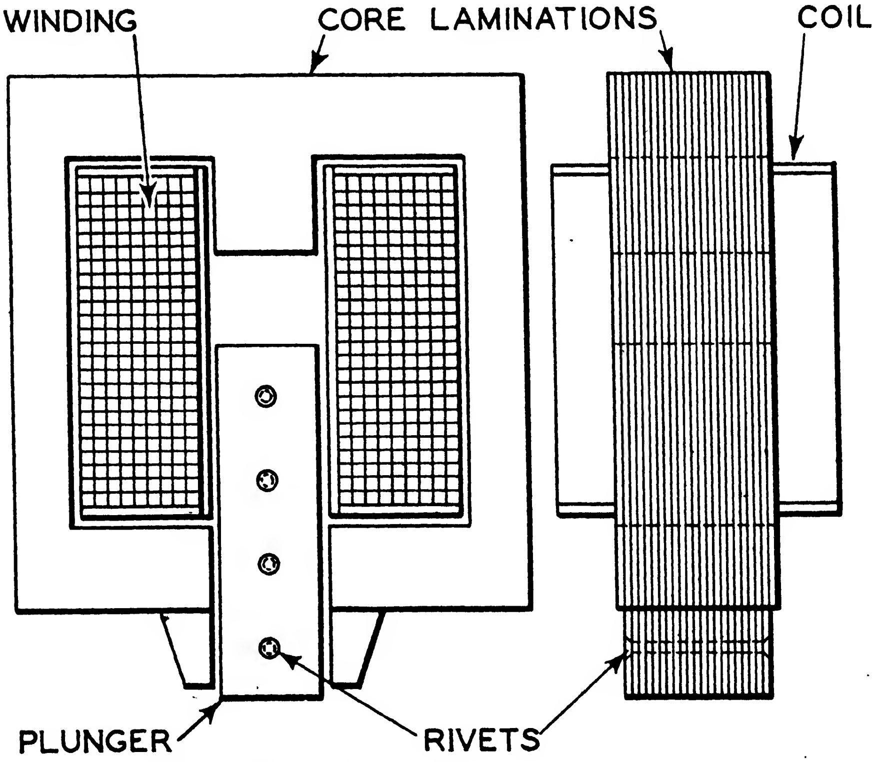

Fig. 17.—Arrangement of laminations in A.C. solenoid. (Clamping plates not shown).

the heat becomes transferred to the coil, so that the temperature of the winding becomes greater than that corresponding to the heating effect of the operating current.

The chief consideration in the selection of stampings for A.C. solenoids is a high specific resistance, so that the heating due to eddy currents is minimised. At the same time, the magnetisation properties must be appropriate to working in the region of $B_{in} = 80{,}000$. Theoretical considerations relating to eddy currents and laminations are given in Chapter I.

A.C. Solenoid Windings

The winding of an A.C. solenoid is subject to the well-known "transformer equation"

$$E = 4{\cdot}44\ BATf10^{-8} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

where B = flux density (lines/sq. inch),
A = cross-sectional area (sq. inches),
T = number of turns in winding,
f = frequency.

From equation (17) it is possible to compute the number of turns required when sufficient other data are available. If, for example, the grade of stampings used permits a flux density of 80,000 lines per sq. inch, and the plunger has a cross-section of 0·75 sq. inches, the number of turns required to operate on a 220-volt, 50-cycle supply would be given by

$$\begin{aligned} T &= \frac{10^8 E}{4{\cdot}44\ BAf} \\ &= \frac{10^8 \times 220}{4{\cdot}44 \times 80{,}000 \times 0{\cdot}75 \times 50} \\ &= 1{,}650 \text{ turns approx.} \end{aligned}$$

As a general empirical rule it is usual to allow about 1 sq. inch of plunger cross-section for every 8 lb. of pull required. The length of the coil should be about 2·5 to 3 times the stroke, and the stop should extend about a quarter of the distance into the coil.

The general form of the magnetic circuit is similar to the D.C. case, except that since laminations are used a shell type construction is not feasible. The field laminations are generally of E-form; the centre leg being short so as to form the stop while the ends of the outer legs have inward extensions as shown in Fig. 17, to give a small gap where the plunger passes through. The laminations are clamped tightly together by means of end plates and bolts, and it is usual for extensions on the end plates to form the fixings for either floor or wall mounting. The rectangular plunger is made of laminations riveted tightly together, and some form of eye-bolt or clevis is fitted for attachment to the load. Guide pieces of brass or similar material are usually employed to locate the plunger so that its motion is free and does not cause friction with the inside of the coil. In this connection it must be remembered that such solid material must not lie in the path of the main flux, or it will overheat owing to the generation of eddy currents.

Design for A.C. Solenoid

We may consider here a tentative design for an A.C. solenoid to lift 10 lb. through a stroke of $1\frac{1}{2}$ inches and to operate on a 400-volt, 50-cycle supply. From the empirical rules above we find that a plunger cross-section of 10/8 = 1·25 sq. inches will be required. On the assumption that $B = 80{,}000$, the coil turns are given by

$$T = \frac{10^8 \times 400}{4{\cdot}44 \times 80{,}000 \times 1{\cdot}25 \times 50}$$
$$= 1{,}800 \text{ turns approx.}$$

The coil length should be between 3·75 and 4·5 in.

The best procedure in connection with the coil after the solenoid has been made is to try an experimental winding of 1,800 turns of wire large enough to give a reasonable depth of winding, say about 1 inch. On the assumption of a plunger with square section, this would give an overall coil size of about $3\frac{1}{4} \times 3\frac{1}{4} \times$ say, 4 inches long. Tests at the rated voltage and frequency will indicate any necessary modifications.

If the pull is insufficient, a few turns should be removed, while if the pull is more than required and the coil overheats, a few more turns should be added.

The final winding should be such that the desired pull is obtained when the voltage is 85 per cent of the rated value and the winding has been left energised at the full rated voltage long enough for a stable temperature to be reached.

If preferred, the coil turns may be calculated on the basis of 0·85 E instead of E in the first place, but the latter value gives a proportion of turns in excess of the theoretical requirements, and it is easier to remove than to add turns to the experimental coil.

It may be noted that in A.C. working the number of turns in the winding is the chief factor. The current, and hence the ampere-turns and flux, are determined by the impedance which depends mainly upon the number of turns and is affected only slightly by the resistance. The cross-section of the wire must of course be large enough to prevent overheating, and the larger the size of wire employed, the cooler will be the coil under operating conditions. In many cases it is good practice to use the largest size of wire which may conveniently be accommodated in the available winding space. The greater weight of wire used is in many cases offset by the fact that larger sizes of wire are cheaper.

A point of considerable importance is the way in which the end of the plunger seats itself against the stop when the solenoid is energised. Smooth and accurately faced surfaces which seat squarely and without gaps not only result in a more complete magnetic circuit, and hence less current, but also operate without objectionable hum and rattle due to the alternating flux.

Shading Coils

Since with A.C. excitation the current passes through zero twice during each cycle, the pull will disappear at these points, and chattering of the plunger against the stop would result. To overcome this effect, use is made of a so-called "shading coil", consisting usually of a single loop or turn of wire or strip embedded in a slot in the face of the stop so as to embrace about two-thirds of the pole area as shown in Fig. 18. This loop behaves as the short-circuited secondary of a transformer, so that the section of material forming the loop should be large in relation to the coil wire, probably five or six times.

The flux produced by the current induced in the loop will be out of phase with the main flux, so that the resultant flux between the plunger and stop will at no time pass through zero. The loop should be lightly insulated from the iron, and in most cases is pressed into machined slots across the face of the stop.

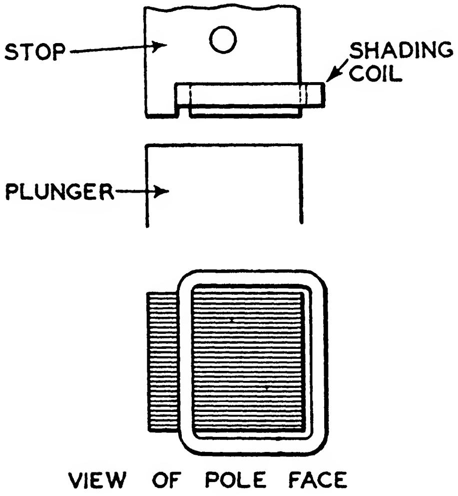

Fig. 18.—Arrangement of shading coil.

Polyphase Solenoids

Solenoids for operating on two-phase or three-phase supplies are in use, but not nearly so extensively as the single-phase type, which can be used across one phase of a polyphase supply if no single-phase is available.

The polyphase solenoid has a two or three limb laminated frame, according to whether it is designed for two or three phase working. The limbs extend downward, and usually attract an armature having the form of a

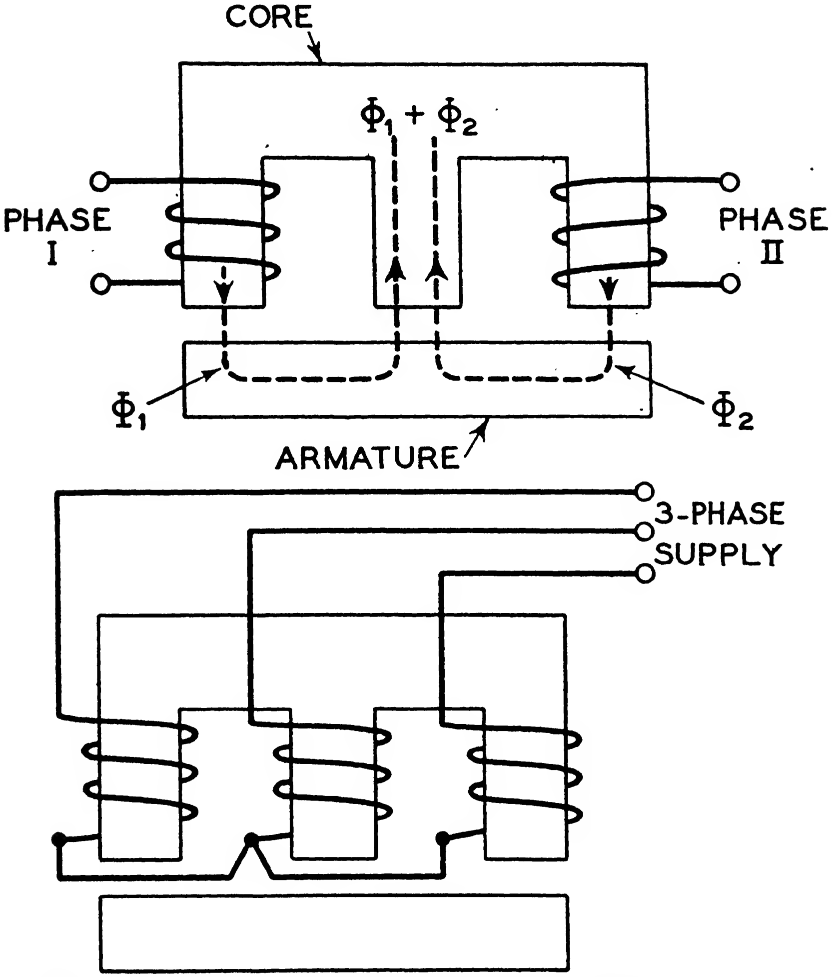

Fig. 19.—TYPICAL ARRANGEMENTS OF TWO-PHASE AND THREE-PHASE SOLENOIDS.

laminated rectangular bar. Owing to the fact that the currents and fluxes in the respective coils of the winding are out of phase with each other, some pull is always being exerted on the armature, so that in general the polyphase solenoid is quieter in operation than the single-phase type and requires no shading coils. The arrangement of typical polyphase solenoids is shown in Fig. 19.

Some designs virtually represent a combination of two or three single-phase solenoids arranged so that their combined pull is exerted on a single eye-bolt or clevis. In all cases it is usual to employ one coil per phase.

Chapter IV

DESIGN OF WINDINGS

THE different coverings obtainable for magnet wire are fairly numerous, since they include enamel, cotton, silk, paper, asbestos, glass, and various combinations of these materials, such as cotton or silk with enamel. Of these types of covering the most suitable for general purposes is undoubtedly enamel, which is relatively inexpensive and compares favourably with most other types in the matter of insulating properties. There are, however, a number of points concerning enamelled wire which represent serious pitfalls for the coil designer, and which may well be considered here.

It may firstly be pointed out that the chief properties required of the covering of wires for coil winding are uniformity of thickness and quality, toughness in order to avoid damage, moisture proofness, high dielectric strength, freedom from holes, and resistance to the effects of temperature so that the properties are maintained under all likely operating conditions.

Enamelled Wire

Enamelled wire has by far the most extensive sphere of application. It is relatively inexpensive, has a thin covering, will withstand high temperatures, of the order of 100°C., without injury, is non-hygroscopic, and has a high dielectric strength. The latter averages about 600 volts per mil, and is about four times as high as silk.

With regard to disadvantages, it may be mentioned that enamelled covering is rather prone to the formation of pinholes during manufacture, and these may prove troublesome in certain cases. The covering is also attacked by solvents such as alcohol, shellac varnish, turpentine, as well as certain animal and vegetable oils. As it is usually only in connection with impregnating processes that such materials come in contact with the wire, this point is relatively unimportant, provided that only impregnating materials which are free from solvents of this kind are employed. Otherwise there is a tendency to short-circuited turns, owing to softening of the enamel film.

There is a British Standard Specification on the subject of Enamelled High-Conductivity Annealed Copper Wire (No. 156–1936), which will serve as a basis for our comments. In this specification chemical tests are described, their object being to determine any action of chemicals upon the enamel covering.

The chemicals specified for the tests are respectively absolute alcohol and sulphuric acid (sp. gr. 1·25 at 15·6°C.). It is stated that after immersion for one hour at a temperature between 10°C. and 27°C. the samples shall not show any signs of cracking or peeling of the enamel after being elongated or wound on a mandrel of specified diameter. It will be realised that such a test does not take into consideration the possibility of softening of the covering, which is much more likely than cracking or peeling after the specified treatment.

Softening of Enamel Wire

The softening of enamel wire covering is a question which has not received due attention up to the present, and which has caused a considerable amount of trouble. This arises in the numerous cases where the windings are impregnated at some stage of manufacture. The impregnating compounds in use for this purpose often contain a solvent which affects the enamel covering of wires in much the same way as it affects the materials used in the manufacture of the compound, i.e., it dissolves them.

It follows when such compounds are used for impregnating purposes that there is a tendency for the covering to soften, with the inevitable result that the insulating properties of the wire are affected. If, as is usually the case, a considerable pressure exists between adjacent turns of the winding, there will be considerable risk of such turns becoming short-circuited.

Such risks must not be entertained under any circumstances in the case of A.C. coils, in which short-circuited turns are usually disastrous, resulting eventually in a complete burn-out. Layers of thin paper are sometimes introduced between successive layers of wire in coils of enamelled wire with the object of preventing trouble of this kind.

Testing Samples of Enamelled Wire

Some enamelled wires at present on the market are particularly bad in respect of attack by ordinary solvents. A good check on the respective properties of different makes can be made by placing samples of the wire in test tubes containing a quantity of the impregnating compounds which it is proposed to employ.

In some cases it is possible to remove the enamel covering readily between the fingers after an immersion of about half-an-hour. In other cases the film appears to be as firm and hard as it was before immersion, even when the immersion period is extended for several hours.

It must not be thought, however, that this is the sole criterion of a good enamelled wire. Resistance to solvent attack is often a characteristic of enamel films which are too brittle to meet the requirements of the British Standard Specification. This states that after winding one layer of contiguous turns on a hard mandrel 1 inch in diameter, it shall not be possible to remove the enamel from the wire by scraping the thumbnail along the length of the wire in the direction of winding. Other tests, of elongation or bending to small radius, according to the wire diameter, are specified for wires of a given bare diameter.

Unless these requirements are met, the wire is not suitable for coil winding, since the covering is likely to fracture during the process. It will be appreciated, therefore, that resistance to solvent effects must not be obtained at the expense of undue tendency to cracking, due to hardness of the enamel film.

Other Coverings

Silk- and cotton-covered wires differ from enamelled wires mainly in the fact that their covering is hygroscopic, unless impregnation is carried out, but they are unaffected by solvents. Silk wire is relatively expensive, and at the present time there are few applications which necessitate the use of silk-covered wires in preference to enamelled or cotton-covered. There is, of course, an advantage of silk over cotton covering in the matter of space-factor.

With regard to silk- and cotton-covered wires, there is comparatively little to say. They differ from enamelled wire mainly on the score that

TABLE II

RADIAL THICKNESS OF INSULATION OF DIFFERENT KINDS OF WIRE COVERING

For 20 s.w.g. (0·036 inch diam.)

Kind of Wire Covering.	*Radial Thickness of Insulation (mils.).*
Single Silk	1·00
Enamel	1·25
Double Silk	1·50
Enam. and S.S.C.	2·25
Single Paper (Special Fine)	2·50
Single Cotton (Special Fine)	2·50
Enamel and D.S.C.	2·75
Single Paper (Ordinary)	3·00
Single Cotton (Ordinary)	3·00
Double Paper (Special Fine)	3·50
Double Cotton (Special Fine)	3·50
Enamel and S.C.C. (Special Fine)	3·75
Enamel and S.C.C. (Ordinary)	5·00
Enamel and D.C.C. (Special Fine)	5·00
Double Paper (Ordinary)	5·50
Double Cotton (Ordinary)	5·50
Enamel and D.C.C. (Ordinary)	7·00
Treble Cotton (Special Fine)	8·00
Treble Cotton (Ordinary)	10·00

they will not withstand such high operating temperatures without disintegrating, and they are generally more expensive. Cotton and silk coverings are also absorbent, and the presence of moisture will seriously affect the resistance of the dielectric between turns unless an effective means of moisture-resisting impregnation is used. Only silk-covered wires can compare favourably with enamelled wire in the matter of insulation thickness.

It is instructive to compare the relative thickness of insulation on the different kinds of wire. Table II (on p. 52), showing the radial thickness of insulation for a variety of different wires refers to a particular size: 20 s.w.g. (0·036 inch diameter bare), and is representative of general practice.

The list is arranged in order of increasing thickness of insulation, so that the wires towards the bottom of the list take up more space in a winding of a given number of turns than those towards the top. This consideration is of obvious importance in the design of all types of coil winding.

Impregnated Wires

Wires having an impregnated covering, usually cotton, are available for use in cases where impregnation after winding is not carried out, but where it is desired to prevent entry of moisture. In general, the use of such wire may be quite satisfactory for armature winding and similar purposes, but there is little to recommend it for coil windings if adequate means of impregnation after winding are available. Before impregnated wire is used it is advisable to conduct tests on sample lengths to determine their behaviour under the effects of bending and abrasion, since some types of impregnating varnish render the covering very hard and brittle.

Manufacturing Limits of Size

In the design of coil windings and the use of data concerning wires, it must be borne in mind that limits of size variation must be allowed owing to manufacturing considerations. A variation of size, or cross-section, means a corresponding variation in electrical resistance, and since the resistance is proportional to the square of the wire diameter, it is evident that considerable latitude must be allowed in practice in the matter of resistance for a nominal size of wire.

The nature of the variations to be allowed for may be seen from the figures in Table III (on p. 52), taken from B.S.S. No. 156–1936.

It will be noticed that the tolerance on the nominal value of resistance in the case of the finer wire is considerably greater than that corresponding to the larger wires. For the 0·002 inch diameter wire the tolerance is no less than 15 per cent, whereas for the other three sizes quoted in the above example the respective tolerances are 4·8, 4·3, and 4·1 per cent.

It is seen that, particularly in the case of fine wire coils, considerable allowance must be made for variations in the expected value of wire resistance.

TABLE III

RESISTANCE TOLERANCE OF COPPER WIRES

Nominal diameters of bare wire. (*inch*).	*Resistance per* 1,000 *yards.*		
	Standard (*ohms*).	*Maximum* (*ohms*).	*Minimum* (*ohms*).
0·0020	7642	8788	6496
0·0108	262·1	274·7	249·5
0·0280	38·99	40·67	37·31
0·0840	4·332	4·510	4·154

Aluminium as a Coil Conductor

The use of aluminium as an electrical conductor has increased considerably during recent years, mainly in those countries where an alternative to copper is desired for economic reasons. The light weight of the metal and its fairly good electrical conductivity have led to its use in coil windings to a limited extent, but up to the present there is no prospect of the widespread adoption of aluminium for this purpose.

It is of interest to note that aluminium has been used in the coil windings of large lifting magnets as shown in Fig. 20, with the object of conserving weight and thus increasing the useful load handled by the magnet. This, of course, is a specialised application, as are most of the other cases where aluminium is used as a coil conductor.

Table IV shows the principal properties of aluminium and copper, and serves to indicate the possibilities of aluminium for coil windings:

TABLE IV

PROPERTIES OF ALUMINIUM AND COPPER

	Aluminium.	*Copper.*
Specific weight (g./cm.^{3})	2·7	8·9
Electrical resistance at 20°C. (microhms/cm.^{3})	2·82	1·72
Resistance temperature-coefficient	0·004	0·0038
Melting-point (°C.)	658	1083

An aluminium conductor has a cross-section 60 per cent greater than that of a copper conductor of the same length and resistance, although its weight will only be about one-half that of the copper conductor.

The insulating properties of aluminium oxide have been utilised with some success for aluminium wire and strip having no other insulation.

Fig. 20.—Aluminium coil in 43-inch lifting magnet.
(*General Electric Co., Ltd.*)

The thin film of oxide is highly resistant to moisture and chemical attack, but like enamel, may require reinforcement between layers in some cases. Good results have been obtained by passing the bare aluminium wire through a solution of sodium hydroxide during winding. Current is then circulated in the winding so as to cause heating. At the beginning of this process, the winding is practically short-circuited, but as the moisture is driven off the insulation improves until finally an adequate insulation resistance is obtained.

Insulation of Windings

It would be difficult to over-estimate the importance of insulation in the manufacture of coils of all kinds. Coil insulation not only has to withstand the conditions imposed upon it in the various processes of coil manufacture, but is often called upon to operate under very exacting conditions, caused by high temperature, dampness or mechanical vibration. There is the added consideration that in some cases it is necessary to deal with abnormal voltages, which have no definite relationship to the operating voltage.

It is of great importance to employ in coil winding only insulating materials which retain their properties after long periods at elevated temperatures. The temperature in the interior of a coil may be very much higher than might be expected from a determination of its external temperature.

A useful principle in the selection of insulating materials is to employ a number of different materials, each with widely different characteristics, rather than to rely upon only one or two. This principle is borrowed from machine-winding practice.

In the case of armatures, for example, it is customary to use at least two different types of slot insulation. The one placed nearest the iron is of tough composition, such as presspahn or leatheroid, which is well able to resist mechanical abrasion, while the inner layer or layers can be of a less robust material, but one having high dielectric strength, such as empire cloth or oiled silk. A similar procedure should be followed in ordinary coil windings, especially of the former-wound variety.

The range of materials available for coil insulation includes the various kinds of pressboard, varnished cambric, mica, micanite, mica-paper and cloth, and oiled silk or cotton (empire cloth). The dielectric strength of mica may be taken as about 800 volts per mil., mica-paper or cloth 400 volts per mil., and empire cloth 600 volts per mil.

Types of Coil Windings

Coils may differ very widely in appearance and construction, but there are relatively few different methods of winding. Practically all coils are wound by one of the following methods:

(a) On a suitably shaped "former", usually with end cheeks. The coil is removed from the former after winding and finished by means of taping or other suitable covering.

(b) On a bobbin which forms an integral part of the coil when finished, and consists either of a suitable moulding or a fabricated construction of insulating material.

(c) By means of special machinery which feeds in with the wire some kind of insulation, in the form of either cotton or paper, in such a way as to make the winding self-supporting. There is in this case no necessity for a former or bobbin.

Mouldings Used for Coil Winding

In some cases bobbins are manufactured, so as to avoid the charges for dies necessary for moulding work, but in general there are alternative methods available which are preferable either on the score of cheapness or superior finish.

With the present variety of methods of moulding and materials for this purpose, the designer must carefully specify his requirements, and refrain from the all too common tendency to purchase on a price basis. Mouldings with high electrical strength and suitable mechanical properties are necessarily expensive, and cheap mouldings should be regarded with suspicion.

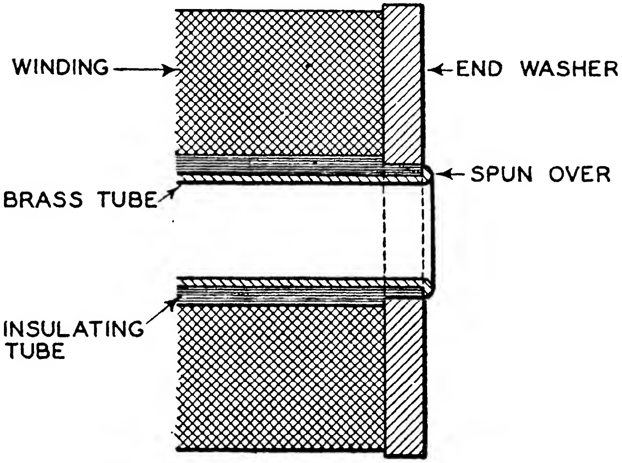

Fig. 21.—Method of fixing coil end washers.

In addition to adequate mechanical strength, mouldings used for coil windings should preserve their mechanical properties at temperatures of the order of 100°C., which are frequently approached with safety in modern coil windings. They should also be non-hygroscopic, as the entry of moisture must be rigidly prevented. Considerable extra cost in the manufacture of moulded coil bobbins is involved with any departure from a simple design. It is rarely necessary to use specially shaped bobbins, and the economic advantage of special shapes should be carefully considered before such shapes are specified.

When bobbins are fabricated, it is very necessary to ensure that the end washers are rigidly attached to the tube. The strains set up in the coil during winding and in service may be considerable, and loose end washers invite coil failure due to mechanical collapse or ingress of moisture. A sound mechanical construction can be made by shouldering the tube and using a brass liner, spun over at the ends to hold the washers in place, as shown in Fig. 21. However, the use of a metal liner affects the operation of the coil, and is not always permissible, as will be shown in Chapter V.

Former-Wound Coils

The former-wound coil is usually cheaper than the bobbin-wound type, although in general it is less robust. The labour involved in the manufacture of former-wound coils is an important consideration from the viewpoint of cost, and it should be borne in mind that a bobbin-wound coil can usually be wound at a higher speed, and therefore more cheaply in so far as the winding itself is concerned. The finishing of a former-wound coil is usually a more lengthy procedure, especially if considerable dielectric strength is required.

In some cases, where a coil is required to have a shape that cannot readily be wound direct, there is a temptation to wind some suitable intermediate shape and to distort this after winding. This practice, although permissible in the case of armature and similar coils wound with a few turns of heavy wire, must be thoroughly condemned for ordinary practice. Considerable strains are likely to be set up in the winding during the forming process, and will be very harmful to insulation of the wire.

For such treatment, which should be avoided wherever possible, only triple covered cotton or silk wire, or wire having a cotton or silk covering over enamel, can be regarded as affording any degree of safety. In most cases the extra cost of such wires would make it more economical to use a suitably designed former or special winding arrangements.

Coil-Winding Machines

Among the types of coil that do not strictly belong to either of the foregoing are those produced by coil-winding machines. These are usually self-supporting coils, and are characterised by cheapness and uniformity of production. In some types, enamelled wire is used exclusively, and the machine introduces into the winding one or more threads of cotton, so controlled as to build up automatically a supporting cheek of cotton at each end of the coil. The thread also traverses the coil during the winding process in such a manner as to bind the turns together and form a cushioning medium between consecutive layers of the winding.

Coils of this kind can be finished off by a layer of cotton in the machine after winding, but owing to the somewhat soft and resilient construction imparted by the interwoven cotton it is necessary to use some impregnating process that will provide a hard finish and prevent ingress of moisture through the cotton.

Arrangement of Leads

One of the most difficult questions in coil design is the disposition, type and arrangement of the terminals. Flexible leads are often used and have evident advantages, but they present difficulties of construction. In order to obtain adequate mechanical strength, the leads should be secured at more than one point.

If, for example, the outer lead is simply bound in with the covering, in the case of a former-wound coil, it will generally be incapable of withstanding mechanical strain. As a rule, the leads should each be capable of sustaining the weight of the coil. Insulation problems are also encountered, especially with the inner leads of coils.

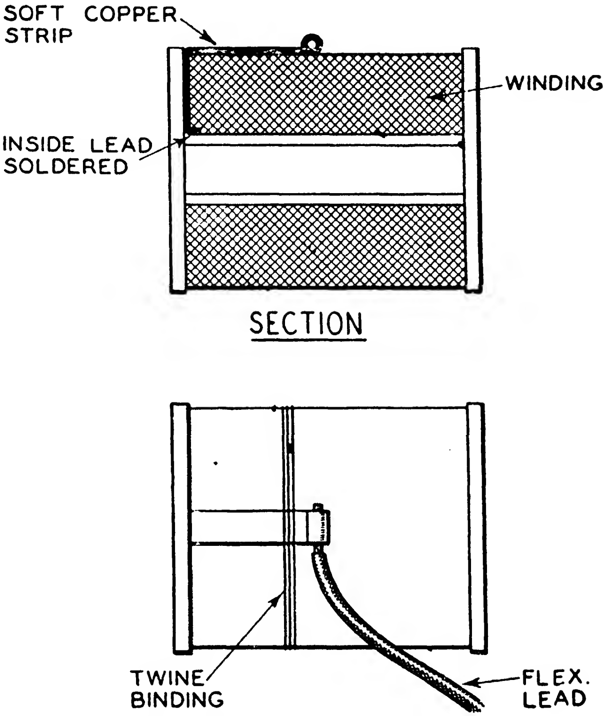

Fig. 22.—METHOD OF ATTACHING FLEXIBLE LEADS FOR INNER WIRE.

In the case of flexible leads it is possible to use a flat strip conductor, which may be effectively insulated from the bottom of the coil, for the inner lead. The flexible may be soldered into a loop in this strip on the surface of the coil as shown in Fig. 22. In some cases lugs or terminals are fixed to the coil for connection purposes. This arrangement is generally reserved for large coils where adequate space is available on the surface of the coil for securing the connectors. Some such arrangement may also be necessary if the current carried by the coil would require the use of an unduly large flexible.

In the case of A.C. coils, particular care must be taken to avoid short-circuiting any turns when leads are connected. The practice of soldering the lead wire to several turns of the winding in order to ensure mechanical security must on no account be used in A.C. coils, since these turns would act as the short-circuited secondary of a transformer and cause destructive overheating.

Foremost among the causes of coil breakdown on D.C. circuits is the inductive rise of voltage across the coil terminals when the coil circuit is opened. The magnitude of this inductive "kick", as it is sometimes called, depends upon various factors, including the number of turns in the coil and the speed with which the circuit is opened.

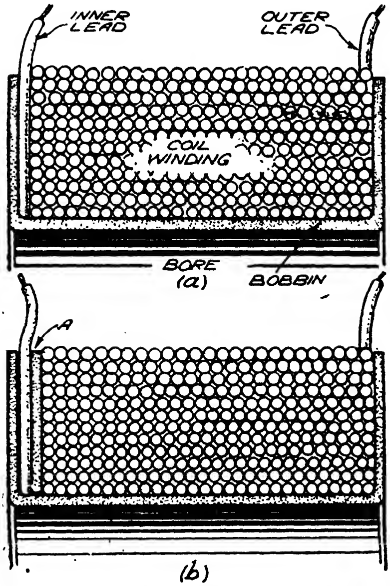

Fig. 23.—HALF-SECTION OF BOBBIN-WOUND COIL.

(*a*) Shows inner lead without protection.

(*b*) Shows inner lead protected by additional insulation at *A*.

It may be mentioned that the inductive voltage rise at switching off a contactor operating coil, for example, may reach ten times the normal operating voltage, or even more in some cases. It is evident that any estimates of insulation requirements based on the operating voltage would be quite inadequate in this case.

One of the most vulnerable points in a coil winding from the viewpoint of inductive kick is the entry of the inside lead, which must usually be brought to the top of the coil, and therefore comes close to the various successive layers of the winding. Any difference of potential across the coil ends or terminals will be virtually applied to the insulation of the inside lead, so that to take care of abnormal voltages it is necessary to give particular attention to this insulation. In many cases it is possible to introduce an insulating washer for this purpose, as shown in Fig. 23.

Soldered Joints

Joints of any kind are to be avoided if at all possible, and in any case cut down to the absolute minimum. All wire ends should be tinned before jointing, and a split sleeve, also tinned thoroughly, should be used in cases where the wire is too thick to make a satisfactory twisted joint. Care must be taken to ensure that joints are well made, as many coil failures are caused by breakdown of joints. Low melting-point solders are to be avoided, and on no account should soldering fluxes with a corrosive acid content be used. The latter precaution applies with particular force in the case of fine wire windings, since these wires may readily be eaten through by corrosive action, or so reduced in cross-section that the wire eventually fuses and thus causes an open circuit in the coil.

IMPREGNATION OF WINDINGS

The impregnation of finished windings serves the two-fold purpose of excluding moisture and improving the thermal conductivity of the winding. Methods of impregnation are numerous, but the main principle is to permeate the winding with a compound having good insulating properties, thus supplementing the normal insulation and at the same time protecting the winding.

In many cases, coils are impregnated simply by first heating them, so as to drive out all moisture, and then immersing them in a tank of insulating compound. This crude method is effective only in cases where the operating conditions for the coil are in no way severe.

An Effective Method of Impregnation

For more exacting conditions, and in all cases of first-class manufacture, it is necessary to employ more thorough methods. The following sequence of operations constitutes an effective method of impregnation for practically all classes of windings.

1. Bake the coils thoroughly, so as to ensure liberation of all moisture. The oven should have suitable vents for disposing of vapour, and should preferably be equipped with automatic means for maintaining the desired temperature, which should not materially exceed the appropriate values in Table V. The time of baking depends upon the size of coil, and will rarely be less than half-an-hour.

2. Place the coils in the chamber of a vacuum impregnating plant. (*Note*—If the chamber can be arranged for preliminary heating operation as above, this is preferable.) Draw a vacuum of as near 30 inches as possible, and maintain for at least half-an-hour, depending upon the size of the coils.

3. Admit impregnating compound into the chamber to a depth sufficient to cover all the coils completely.

4. As soon as the coils are covered, release the vacuum and change over to pressure connections, so as to force the compound thoroughly into the coil-windings. The highest practicable pressure should be employed, and maintained for about 15 minutes.

5. Release pressure, withdraw coils from compound, and commence immediately a slow baking process while the coils are draining. The baking temperature should commence at about 40°C. (104°F.), and be increased gradually over a period of at least 1 hour to a final value of about 120°C. (248°F.), which should be maintained for at least half-an-hour.

A high initial baking temperature is undesirable, since it is then possible for the outside of the coils to become hard and prevent liberation of the compound and solvents from the interior.

All methods of impregnation should be established on the basis of proven effectiveness. This can be determined by stripping open sample coils occasionally to find whether the compound has penetrated thoroughly into the winding.

TABLE V

TEMPERATURE LIMITS FOR COIL WINDINGS*

Insulating Material.	*Total Temperature.* (°C.)		*Maximum Temperature-rise.*† (°C.)	
	Shunt Coils.	*Series Coils.*	*Shunt Coils.*	*Series Coils.*
CLASS 0				
Cotton, Silk, Paper, and similar materials (not impregnated)	80	90	50	60
CLASS A				
1. Class 0 materials, impregnated or oil-immersed, or used with enamel. ...	90	100	60	70
2. Enamelled wire not in association with fibrous material	110	120	80	90
CLASS B				
Built-up Asbestos, Mica and similar materials, and bare coils	140	150	110	120
CLASS D				
Coils with synthetic resin impregnation ...	110	120	80	90

* *Taken from B.S.S. No.* 587–1935.

† *If ambient temperature exceeds* 30°*C., temperature-rise must be reduced so that specified total temperature is not exceeded.*

THEORY OF COIL WINDINGS

The types of coil and coil windings encountered in practice vary considerably in size and construction, according to the purpose for which they are intended. The instrument coil wound with many thousands of turns of fine wire, and the lifting-magnet coil wound with relatively few turns of heavy strip, are examples of the diversity of types employed in modern electrical practice.

The proper design of coil windings of all types calls for a knowledge of wires of various kinds and the properties of insulating materials. In the early days of electrical engineering, the construction of coils was a much less scientific procedure than it is to-day. During recent years the practice of coil design and manufacture has been extensively developed until it now forms an important branch of electrical engineering.

The basic rules of coil theory are those relating to the properties of wires of various kinds. In this respect it is fortunate that copper is the metal almost exclusively used for coil-winding purposes, so that we may confine our attention firstly to the properties of copper wires.

Resistance of Wires

It is, of course, very necessary in coil design to know the relationship between the length of a given kind of wire and its electrical resistance, as this relationship enables us to calculate the resistance of any coil from a knowledge of the total length of wire it contains. The length of wire can usually be determined readily from the finished dimensions of the coil and a knowledge of the total number of turns of wire.

The electrical resistance of any conductor of uniform cross-section is determined by three factors as follows:

(1) The length of the conductor.

(2) Its area of cross-section.

(3) The material from which the conductor is made.

There is, strictly speaking, a fourth factor, which is the temperature of the conductor, but at the present stage the effects of temperature upon electrical resistance will be neglected for the sake of clearness.

With regard to the other factors, it may be stated that the resistance of any conductor is:

(a) Directly proportional to its length.

(b) Inversely proportional to the cross-sectional area.

(c) Dependent upon the material from which the conductor is made.

Calculating Resistance of a Given Length of Wire

In order to be able to calculate the resistance of a given length of wire, the above relationships may be expressed by the simple formula :—

$$\text{Resistance of Conductor} = \frac{\text{Length} \times \text{Specific Resistance}}{\text{Area of Cross-section}}$$

or, in symbols, $R = l \times k/a$. The constant k, which is called the "specific resistance", has a different value for each material and represents the electrical resistance of a unit cube of the material, i.e., a cube of unit length and unit cross-sectional area.

It is important to notice that the units of measurement upon which the specific resistance is based must be the same as those of the other dimensions. This means that if l and a are expressed in centimetres, then k must be expressed as the resistance per centimetre cube. If inch units are used, then k must be expressed in terms of an inch cube.

A list of specific resistances of common materials in both systems of measurement is given in Table VI (page 64).

Owing to the extremely small value of k if expressed in ohms, it is usual to quote specific resistance in microhms (millionths of an ohm). The specific resistance of copper, with which we are chiefly concerned, is approximately 1·72 microhms per cm. cube, or 0·68 microhms per inch cube.

TABLE VI

SPECIFIC RESISTANCE OF COMMON MATERIALS

Material.	*Specific Resistance in Microhms.*	
	per cm. cube.	*per inch cube.*
Aluminium	2·82	1·12
Brass	8·0	3·15
Phosphor Bronze	8·0	3·15
Constantan	49·0	19·3
Copper	1·72	0·68
German Silver	28·0	11·0
Iron	9·8	3·86
Manganin	44·0	17·4
Nichrome	100·0	39·4
Nickel	7·24	2·86
Silver	1·62	0·64

All values in this Table correspond to a temperature of 20°C.

To illustrate the use of the resistance formula, we may calculate by its means the resistance of a 100-ft. length of 18 s.w.g. copper wire. Bearing in mind the fact that English units of measurement are being used, we may write—

$$R = \frac{100 \times 12 \times 0{\cdot}68}{0{\cdot}00180 \times 1\,000\,000} = 0{\cdot}45 \text{ ohm.}$$

The multiplying factor of 12 in the numerator is to bring the length to inches, so as to agree with the value of k in inch units. This factor is in millionths of an ohm, so that in order to express the answer in ohms a multiplying factor of one million must be introduced in the denominator. The other factor in the denominator is the cross-sectional area of an 18 s.w.g. wire, expressed in sq. inches (see Table VIII, page 75).

Space Occupied by Winding

For design purposes it is important to know the amount of space required by a given winding, so that the size of the finished coil may be computed. Unless the outside diameter of the coil is known, it is not possible to calculate the resistance, and it is usually necessary that this should be known. For this purpose it is convenient to know the number of turns which can be accommodated per sq. inch of the cross-section of winding for any size and type of wire. This information may be computed in the following manner.

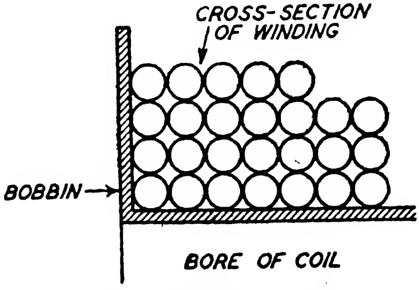

FIG. 24.—VERTICAL PILING OF COIL TURNS GIVING MINIMUM SPACE FACTOR.

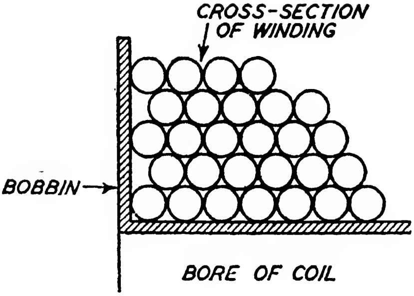

Fig. 25.—USUAL ARRANGEMENT OF COIL TURNS GIVING MAXIMUM SPACE FACTOR.

If D is the diameter in inches over the covering of the wire, then theoretically we should be able to get $1/D$ turns side by side for every inch of the winding length. It is more conservative to deduct, say, 5 per cent from this number of turns, so as to allow for inequalities in the size of the wire and slight inaccuracies in winding. We therefore get for the number of turns per inch of winding length $T = 0{\cdot}95/D$. The number of layers per inch in a vertical direction can be taken as the same as the number of turns per inch horizontally (along the length of the coil).

If the winding is as shown in section in Fig. 24, the number of turns per sq. inch would evidently be $(0{\cdot}95/D)^2$, but because in actual practice it is more likely to be as shown in Fig. 25, there is actually a larger maximum number of turns than this. A factor of 10 per cent* may be introduced to allow for the increase, so that we obtain finally for the maximum number of turns per sq. inch—

$$T = (0{\cdot}95/D)^2 \times 1{\cdot}1 = 0{\cdot}99/D^2 \text{ approx.}$$

If, for example, we consider an 18 s.w.g. enamelled wire having a bare diameter of 0·048 inch, and an overall diameter of 0·0508 inch, the number of turns per sq. inch will be $0{\cdot}990/{\cdot}0508^2 = 0{\cdot}99/0{\cdot}00258 = 384$ approximately. A double cotton-covered wire of the same gauge will have an overall diameter of about 0·059 inch, and application of the formula will show that in this case the maximum number of turns per sq. inch will be approximately 284, or only 74 per cent of the number corresponding to the same gauge of enamelled wire.

Permissible Number of Turns per Square Inch

Table VII, which has been prepared on the basis of the foregoing calculations, shows the maximum permissible number of turns per sq. inch for the three most commonly used kinds of wire, viz., enamelled, single-cotton-covered, and double-cotton-covered. It may be pointed out that the allowances made in the table for thicknesses of cotton insulation correspond to ordinary covering, and not the specially fine cotton coverings, which are considerably thinner. Corresponding particulars for any other size and kind of wire may readily be added to the table if information is available regarding the thickness of covering for the different

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* On the assumption that the wires are incompressible, the theoretical factor is less than 10 per cent., but this value may be allowed so as to cover the compression of the covering at the points of contact, especially in the case of cotton or silk covering.

sizes. This information is usually to be found in the catalogue of any manufacturer of covered wires.

TABLE VII

TURNS PER SQ. INCH OF WINDING SPACE FOR DIFFERENT TYPES OF WIRES

		Enamelled.		*S.C.C.*		*D.C.C.*	
S.W.G.	*Bare Diam.*	*Covered Diam.*	*Turns per sq. inch.*	*Covered Diam.*	*Turns per sq. inch.*	*Covered Diam.*	*Turns per sq. inch.*
10	0·128	0·134	55	0·136	53	0·142	49
11	0·116	0·122	66	0·124	64	0·130	58
12	0·104	0·110	82	0·112	78	0·118	70
*	0·100	0·106	88	0·108	85	0·114	76
13	0·092	0·098	103	0·100	99	0·106	88
*	0·084	0·089 5	124	0·092	116	0·098	103
14	0·080	0·085 0	136	0·088	128	0·094	112
*	0·076	0·080 5	152	0·084	140	0·090	122
15	0·072	0·076 0	170	0·079	158	0·084	140
16	0·064	0·067 5	217	0·071	196	0·076	170
17	0·056	0·059 0	284	0·063	250	0·068	214
18	0·048	0·050 8	384	0·055	326	0·059	284
19	0·040	0·042 5	550	0·047	445	0·051	380
20	0·036	0·038 4	670	0·042	560	0·047	450
21	0·032	0·034 3	840	0·083	680	0·043	535
22	0·028	0·030 2	1 080	0·034	850	0·039	650
23	0·024	0·026 1	1 460	0·029	1 180	0·034	850
24	0·022	0·024 0	1 720	0·027	1 360	0·032	968
25	0·020	0·022 0	2 040	0·025	1 580	0·030	1 100
26	0·018	0·019 8	2 520	0·023	1 870	0·028	1 260
27	0·016 4	0·018 1	3 020	0·021 4	2 160	0·026 4	1 420
28	0·014 8	0·016 4	3 670	0·019 8	2 520	0·024 8	1 600
29	0·013 6	0·015 1	4 350	0·018 6	2 850	0·023 6	1 770
30	0·012 4	0·013 8	5 200	0·017 4	3 250	0·022 4	1 970
31	0·011 6	0·012 9	5 920	0·016 6	3 600	0·021 6	2 120
32	0·010 8	0·012 1	6 750	0·015 8	3 960	0·020 8	2 270
33	0·010 0	0·011 2	7 850	0·015 0	4 400	0·020 0	2 470
34	0·009 2	0·010 3	9 330	0·014 2	4 900	0·019 2	2 670
35	0·008 4	0·009 5	11 000	0·012 4	6 420	0·017 4	3 250
36	0·007 6	0·008 6	13 400	0·011 6	7 320	0·016 6	3 600
37	0·006 8	0·007 8	16 200	0·010 8	8 500	0·015 8	3 950
38	0·006 0	0·006 9	20 700	0·010 0	9 900	0·015 0	4 400
39	0·005 2	0·006 1	26 500	0·009 2	11 600	0·014 2	4 900
40	0·004 8	0·005 6	31 500	0·008 8	12 800	0·013 8	5 200

* *Denotes non-standard sizes.*

It will be realised that a great deal depends upon how the wires lie during winding. Attempts to improve the space factor by tapping the winding with a mallet are likely to result in damage to the wire insulation, and it is much better practice to take care that the wire is wound evenly in the first place. It is scarcely necessary to add that if excessive tension is applied to the wire during winding, with the object of getting the maximum number of turns into the available space, there is considerable risk of stretching the wire, with the result that its resistance for a given length will increase and consequently that the coil resistance will be in excess of the proper figure.

Strip Windings

In the case of some of the coil windings used in practice, it is not convenient to employ conductors of circular cross-section owing to the high value of current in the winding and the consequent necessity for a large cross-sectional area. Very thick wires are naturally difficult to handle, especially when it is desired to produce a neat and compact winding.

A No. 4 s.w.g. wire, for example, having a nominal diameter of 0·232 inch, will carry a current of about 100 amperes in most forms of winding, but is very stiff in handling, especially if the coil diameter is small.

An alternative is to use two smaller wires in parallel, giving an adequate total section. In the example just quoted, it might be possible to use two No. 8 s.w.g. wires in parallel, although this would give an aggregate section of 0·04022 sq. inch as compared with the 0·04227 sq. inch section of a single No. 4 s.w.g. wire.

In all cases where the parallel arrangement of wires is used it must be remembered that the space factor of small wires is not so good as that of large ones, so that it is necessary to check carefully the amount of space required by the winding.

In the case of large lifting magnets, the excitation current may be well in excess of 100 amperes, and currents of this order are frequently encountered in switchgear practice in connection with overload relay coils and magnetic blow-out coils. Conductors of rectangular section are often used for windings of this kind.

Uninsulated Strip Coils

In the case of uninsulated strip coils as used for overload releases and blow-outs, where relatively few turns are used and the current is high, the cross-section of conductor is sufficient to make the coil self-supporting. The number of turns is determined from a knowledge of the ampere-turns necessary to produce the requisite magnetic field strength, as shown in previous chapters.

It may so happen that the number of turns required is one, or even less, as in the case of a current relay, for example, where the operating current is 500 amperes, and the relay operates with 400 ampere-turns. In such a case, one complete mechanical turn may produce too much field, whereas the arrangement shown in Fig. 26, utilising a half-turn, will

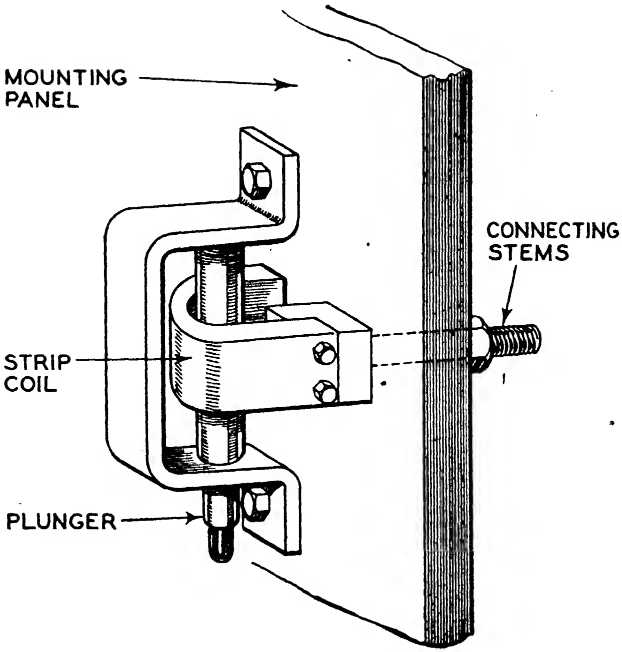

Fig. 26.—USE OF HALF-TURN COIL FOR HEAVY CURRENT.

probably be satisfactory, owing to the considerable increment of flux produced in the iron circuit by the coil sides.

With coils of this particular kind it is not often necessary to calculate the resistance accurately, but this may done if required on the basis of the usual formula—

$$R = lk/a.$$

where l = length of conductor,

k = specific resistance,

a = area of cross-section.

In the case of conductors with rectangular section, the factor a will be represented by the product of width and thickness.

Winding with Rectangular Wire

The space factor of a winding with rectangular wire depends naturally upon the amount of insulation present in the winding. If a covered wire is used, the permissible number of turns per sq. inch of winding section can be readily estimated from a knowledge of the thickness of covering, i.e., the overall dimensions of the covered wire. It is not permissible to assume that the wires will pack together so closely that there is no space between them.

A better plan is to calculate on the basis of a winding length equal to 95 per cent of the actual length available as in the case of round wires, and to use a similar factor for the winding depth. This means that the actual section occupied by the winding, including the conductor insulation, is taken as being about 90 per cent of the total available space. This provision allows for unevenness in the bedding of the conductors and slight variations in thickness of covering.

In some cases coils are made from flat strip which is thin in relation to its width, and a strip of insulating material is wound along with the conductor so as to form insulation between turns and thus obviate the necessity of using a covered strip. The resistance of such a coil is readily calculated from the total length of conductor, which may be estimated from the finished coil dimensions, and the cross-section of the conductor used.

FUNDAMENTAL WINDING CALCULATIONS

The most general problem in coil design is to find the correct size of wire with which to wind a coil of given dimensions in order that it will produce a given number of ampere-turns when connected to a specified supply. In the case of D.C. coils this is a straightforward procedure.

Cylindrical Coil

In the first case we will consider a cylindrical coil in which the dimensions available for the winding are as shown in Fig. 27. It must be emphasised that these dimensions are not the same as the overall measurements of the finished coil, which naturally include an allowance for the covering.

The inner bore of the coil D_2 is usually fixed by mechanical considerations so that the finished coil, including its covering, will be a comfortable fit in the magnetic circuit to which it belongs. The outer diameter D_1 is not fixed, but has an upper limit representing the maximum space available for the coil. In general, it is advisable to work to the maximum value of D_1. This ensures maximum radiating surface of the coil, and therefore results in a lower operating temperature. Although the weight of wire is increased by this process, it does not follow that the cost is increased, since the cost varies with the size of wire. By using the maximum available dimensions it may also be possible to use a wire having greater thickness of covering, so as to obtain a greater factor of safety in insulation.

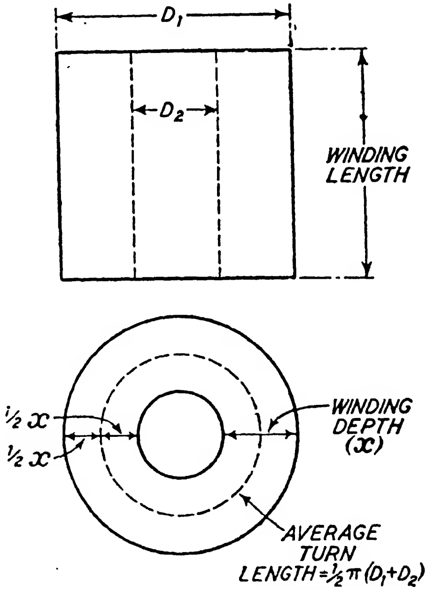

Fig. 27.—PRINCIPAL DIMENSIONS OF CYLINDRICAL COIL.

Trial and Error Method

A trial and error method may be used for arriving at the correct size of wire, the procedure being as follows:

(a) Make arbitrary selection of wire size from a suitable wire table, and compute diameter over covering.

(b) Calculate maximum number of turns which can be accommodated in available winding space.

(c) Find length of average turn of coil $= \frac{1}{2}\pi\ (D_1 + D_2)$.

(d) Find total length of wire = number of turns as found under (b) above, multiplied by the length of average turn as found under (c).

(e) Calculate resistance of coil = total length of wire as found under (d) multiplied by the resistance per unit length of the particular wire; the unit being the same as that used to express the length of wire.

(f) Calculate ampere-turns of coil from the formula :—

ampere-turns $= ET/R$
where E = applied voltage,
T = number of turns,
R = coil resistance.

(g) If the number of ampere-turns calculated in this way is too small, repeat the foregoing process for a wire of larger section, and *vice versa*.

Allowance for Increasing Coil Temperature

It is necessary to bear in mind that the coil temperature will increase under operating conditions, and since this increase of temperature will result in an increase of resistance, the ampere-turns will be reduced for a given applied voltage. For this reason it is necessary to allow a margin over the required number of ampere-turns, so that when the coil has reached its maximum temperature and resistance the number of ampere-turns will still be sufficient. In most cases it is sufficient to allow a factor of about 25 per cent more than the required number of ampere-turns.

An Alternative Method

An alternative method is available for making a first approximation to the size of wire required in order to eliminate the somewhat laborious steps in the approach to the final answer. This alternative method makes use of a formula based upon the relationship between the various properties of a winding, and which may be derived as follows:

In any cylindrical coil, the length of average or mean turn is given by

$$l_m = \tfrac{1}{2}\pi\ (D_1 + D_2) \qquad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$= \pi \times \text{average between inner and outer diameters.}$$

The length of wire in the coil, expressed in the same units as D_1 and D_2 are measured, is then

$$l_m T = \tfrac{1}{2}\ T\pi\ (D_1 + D_2) \qquad . \quad . \quad . \quad . \quad . \quad (19)$$

where T is the number of turns.

The resistance of the coil is equal to the length of wire times the resistance per unit length of wire in appropriate units. If D_1 and D_2 are expressed in inches, then the resistance per inch length is the unit required, and is given by the usual formula :—

$$r = kl/a \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

Taking $k = 0{\cdot}68$ microhms per inch cube for copper, this formula reduces to

$$r = \frac{0{\cdot}68}{\frac{1}{4}\pi d^2\, 10^6} \text{ ohms per inch} \quad . \quad . \quad . \quad . \quad (21)$$

for a wire of circular cross-section, d inches in diameter.

The resistance of the coil is then given by the following equation, derived from (19) and (21) above:

$$R = \frac{\frac{1}{2}T\pi\,(D_1 + D_2)\,0{\cdot}68}{\frac{1}{4}\pi d^2\,10^6} \quad . \quad . \quad . \quad . \quad . \quad . \quad (22)$$

$$= \frac{1{\cdot}36\,(D_1 + D_2)\,T}{d^2\,10^6}$$

We know that for any coil

$$\text{ampere turns } (IT) = ET/R \quad . \quad . \quad . \quad . \quad (23)$$

so that we have

$$IT = \frac{ET\,d^2\,10^6}{1{\cdot}36\,(D_1 + D_2)\,T} \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

from which we find that

$$d^2 = \frac{1{\cdot}36\,IT\,(D_1 + D_2)}{E\,10^6} \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

and

$$d = \sqrt{\frac{1{\cdot}36\,IT\,(D_1 + D_2)}{10^6\,E}} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

or alternatively

$$d = \frac{1{\cdot}17}{10^3}\sqrt{\frac{IT\,(D_1 + D_2)}{E}} \quad . \quad . \quad . \quad . \quad . \quad (27)$$

This equation gives the bare diameter of the wire necessary for a coil of outside and inside diameters D_1 and D_2 respectively and operating on a voltage E in order to produce a given number of ampere-turns (IT).

It will be understood that for aluminium wire coils, the value of 0·68 in the foregoing formulæ has to be replaced by the corresponding figure for aluminium, which is about 1·11, giving a final value of d nearly 30 per cent greater than that for copper.

Having decided upon the size of wire, and checked through the calculations as for the step-by-step method already described, it may be necessary to go up or down a gauge or two in order to get the best results, bearing in mind the allowance necessary on ampere-turns to cover the effect of temperature rise.

It will be understood that exact compliance with equation (27) is rarely possible, owing to the definite steps in size represented by the standard wire gauge.

The Effect of Space Factor

The space factor may be defined as the ratio of the aggregate cross-section of the conductors in a winding to the total winding space occupied by the winding. It is therefore expressed by $z = aT/A$, where a is the cross-section of wire, T the number of turns and A the winding section. This latter quantity is also equal to Lx, the product of winding length and depth of winding. In any D.C. coil, the ampere-turns, current density in the wire, and space factor are related as follows:

$$A = Lx = \frac{IT}{(\text{Amps./sq. inch})\, z} \quad . \quad . \quad . \quad (28)$$

This will be seen by putting the formula in the form

$$A = \frac{IT}{(I/a)\,(aT/A)} = \frac{ITaA}{ITa}$$

It is evident from Table VII that the space factor varies considerably with the size of wire, being small for small wires and *vice versa*. If now we assume a definite value of current density, e.g., 1000 amperes per sq. inch, it will be seen from formula (28) that 1 sq. inch of winding section will give $A = 1 = \frac{IT}{1000z}$. If $z = 0{\cdot}5$, for example, we have $1 = IT/500$, so that with this current density and space factor the winding will produce 500 ampere-turns per sq. inch of winding section. It follows that a high value of z, such as corresponds to enamelled wire, gives more ampere-turns in a winding of given size with a given current density. Formula (28) is very useful as a means of making an approximation to the cross-section of winding required to produce a certain number of ampere-turns. In this case it is usual to assume a value of approximately 1000 amps./sq. inch for the current density for continuous duty applications.

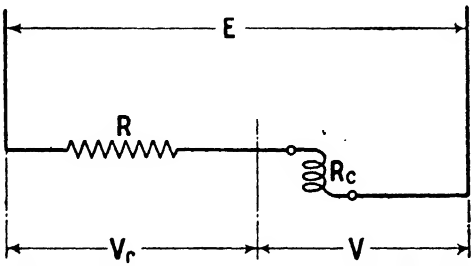

Fig. 28.—OPERATION OF COIL IN SERIES WITH RESISTANCE.

Coils in Series with Resistance

In many cases it is necessary to operate a coil on a supply of higher voltage than for which the coil was designed. This can be done by connecting the coil to the supply in series with a resistance of such a value as to produce a voltage drop equal to the difference between the supply voltage and the voltage on which the coil is designed to operate.

The circuit is shown in Fig. 28, where R is the series resistance, R_c the coil resistance, E the supply voltage, and V_r and V the respective voltage drops across the two branches of the circuit. The current in the circuit is given by $V/R_c = I$, and the total circuit resistance must consequently be E/I, so that the series resistance is $(E/I) - R_c = R$. Substituting for I gives finally

$$R = \frac{ER_c}{V} - R_c,$$

and from this formula the required value of series resistance may be calculated when the supply voltage, coil resistance and permissible coil voltage are known.

As an example, we may suppose that a coil of 500 ohms resistance with an operating voltage of 100 volts is required to operate on a 400-volt supply. This means of course that 300 volts must be dropped on the series resistance. Substituting in the formula, we find that

$$R = \frac{400 \times 500}{100} - 500 = 1500 \text{ ohms.}$$

To check the correctness of this figure we may note that the circuit current is equal to $V/R_c = 100/500 = 0{\cdot}20$ ampere, and that the drop on the series resistance is $IR = 0{\cdot}20 \times 1500 = 300$ volts. The size of resistor required for R will be determined by the watts dissipated in it, which are given by I^2R or $(E - V)^2/R$. In the case considered, the watts will be $0{\cdot}20^2 \times 1500 = 60$ watts, or the same answer may be obtained by using the alternative expression, giving $(400 - 100)^2/1500 = 60$ watts. The resistor must be rated to carry 60 watts continuously only if the circuit remains closed for periods longer than that corresponding to the heating time of the resistor. It will also be noted that the coil voltage need not necessarily be the permissible continuous voltage if the circuit is closed only for short periods.

These considerations do not apply to A.C. circuits, where the use of a series resistance for reducing coil voltage is rarely encountered. Since in an A.C. electromagnet the current is usually very much greater when switching on than when the iron circuit is completed by the plunger or armature, the use of a series resistance is accompanied by complications which cannot always be overcome satisfactorily.

Change of Coil Voltage

It will be noted from formula (27) that for a given size of coil and number of ampere-turns, the terms on the right-hand side are all constants, so that we may write for the diameter of the wire

$$d = \sqrt{\frac{k}{E}}.$$

For a coil of the same dimensions and ampere-turns, but different voltage, E_1, the diameter of wire will be given by

$$d_1 = \sqrt{\frac{k}{E_1}}.$$

We have therefore

$$\frac{d}{d_1} = \frac{\sqrt{k}}{\sqrt{E}} \cdot \frac{\sqrt{E_1}}{\sqrt{k}} = \frac{\sqrt{E_1}}{\sqrt{E}},$$

from which relationship it is possible to arrive quickly at the size of wire necessary for a coil to give the same ampere-turns as another *of the same dimensions* but designed for a different voltage. Supposing, for example, that a given coil has a working voltage of 100 volts and is wound with 20 s.w.g. (0·036 inch diam.) wire, and that it is desired to produce a coil of the same dimensions to produce the same ampere-turns on a voltage of 225 volts, we have

$$\frac{d}{d_1} = \frac{\sqrt{E_1}}{\sqrt{E}} = \frac{\sqrt{225}}{\sqrt{100}} = \frac{15}{10} = 1{\cdot}5$$

so that the diameter of the wire which must be used for the new coil is immediately given by

$$d_1 = d/1{\cdot}5 = 0{\cdot}036/1{\cdot}5 = 0{\cdot}024 \text{ inch}$$

From Table VIII it will be seen that this corresponds exactly to the diameter of 23 s.w.g. wire. In most cases it will be found that the size calculated in this way falls between two standard sizes. It should then be remembered that the larger wire will give more ampere-turns, and more heating, than the original coil, and *vice versa.*

Weight of Wire Required

The weight of wire required may be readily computed from the known length of wire in the coil and the weight per unit length as given in Table VIII. An alternative method, which is useful as a check, is to multiply the actual volume of metal in the coil by the specific weight.

TABLE VIII

DATA FOR ROUND COPPER WIRES

S.W.G.	*Diameter (inches).*	*Area (sq. inches).*	*Lb. per 1,000 yds.*	*Ohms per 1,000 yds.*	*Ohms per lb.*
10	0·128	0·012 9	148·82	1·866	0·012 5
11	0·116	0·010 6	122·22	2·272	0·018 6
12	0·104	0·008 5	98·24	2·826	0·028 8
*	0·100	0·007 8	90·83	3·057	0·033 6
13	0·092	0·006 6	76·88	3·612	0·047 0
*	0·084	0·005 5	64·09	4·332	0·067 6
14	0·080	0·005 0	58·13	4·776	0·082 2
*	0·076	0·004 5	52·46	5·292	0·100 9
15	0·072	0·004 0	47·09	5·897	0·125 2
16	0·064	0·003 2	42·00	6·611	0·157 4
17	0·056	0·002 4	28·48	9·747	0·342 2
18	0·048	0·001 8	20·93	13·267	0·634 0
19	0·040	0·001 2	14·53	19·105	1·314
20	0·036	0·001 0	11·77	23·59	2·004
21	0·032	0·000 80	9·30	29·85	3·209
22	0·028	0·000 616	7·121	38·99	5·475
23	0·024	0·000 452	5·232	53·07	10·144
24	0·022	0·000 380	4·396	63·16	14·36
25	0·020	0·000 314	3·633	76·42	21·03
26	0·018	0·000 254	2·943	94·35	32·06
27	0·016 4	0·000 211	2·443	113·65	46·52
28	0·014 8	0·000 172	1·990	139·55	70·14
29	0·013 6	0·000 145	1·680	165·27	98·37
30	0·012 4	0·000 120	1·397	198·80	142·35
31	0·011 6	0·000 105	1·222	227·2	185·87
32	0·010 8	0·000 091 6	1·059	262·1	247·4
33	0·010 0	0·000 078 5	0·908 3	305·7	336 5
34	0·009 2	0·000 066 4	0·768 8	361·2	469·8
35	0·008 4	0·000 055 4	0·640 9	433·2	676·0
36	0·007 6	0·000 045 3	0·524 6	529·2	1 008·7
37	0 006 8	0·000 036 3	0·420 0	661·1	1 574·0
38	0·006 0	0·000 028 3	0·327 0	849·1	2 597
39	0·005 2	0·000 021 2	0·245 6	1 130·5	4 603
40	0·004 8	0·000 018 1	0·209 3	1 326·7	6 340

* *Denotes non-standard sizes.*

TABLE IX

WEIGHT OF INSULATION ON WIRES

Size (S.W.G.)	*Approximate increase of weight due to Insulation (per cent).*	
	Enamelled.	*S.C.C.*
12	0·6	1·3
21	1·6	4·0
33	2·2	15·0

The additional weight represented by the covering is small in most cases, except in the smaller sizes of wire. The approximate increase of weight due to the covering in the case of three widely different sizes of wire is shown in Table IX, which will serve as a guide when specifying quantities of wire required, although it will be understood that the weight of insulation varies considerably with quality and thickness.

Rectangular Coils

In the case of rectangular coils, the procedure in design is similar, and a first approximation to the size of wire may be made on the basis of equation (27) by taking values of D_1 and D_2 corresponding to the diameter of circles whose circumference is equal to the sum of the sides corresponding to the rectangular coil. The length of average or mean turn is, of course, equal to half the sum of the inside and outside perimeters of the coil.

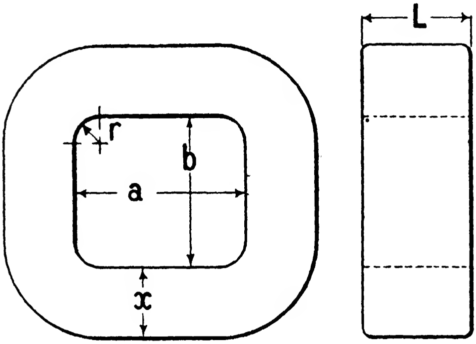

Fig. 29.—PRINCIPAL DIMENSIONS OF RECTANGULAR COIL.

If accuracy is required, reference may be made to Fig. 29, in which a and b represent the internal dimensions of the winding (excluding the insulation), r is the radius of the corners and x the depth of winding. For the length of average or mean turn we have

$$\begin{aligned} l_m &= \pi(x + 2r) + 2(a - 2r) + 2(b - 2r) \\ &= \pi x + 2(a + b) - 1{\cdot}72r \end{aligned}$$

If the core is square, $a = b$, and

$$l_m = \pi x + 4a - 1{\cdot}72r$$

In a similar way it can be seen that the area of the curved external surface of a rectangular coil is given by

$$A = [2\pi x + 2(a + b) - 1{\cdot}72r]\, L,$$

while if the core is square,

$$A = (2\pi x + 4a - 1{\cdot}72r)\, L,$$

where L is the length of the coil.

Design of Series Coils

In some cases electromagnets are operated in series with another device instead of directly across the supply. An example of such use is an electromagnet operating a brake and working in series with a motor, so that the motor current passes through the electromagnet winding. It is evident that in this case the coil must have sufficient turns to operate with the minimum current taken by the motor, and must also be of sufficiently low resistance to ensure that the heating remains at a safe value when maximum current is passing. This means that if $I_{max.}$ and $I_{min.}$ represent the maximum and minimum values of current respectively, and (IT) the number of ampere-turns required to operate the electromagnet, then the turns required are given by

$$T = (IT)/I_{min.}$$

while the number of watts dissipation for which the coil must be designed, is equal to

$$W = I^2_{max.} R,$$

where R is the coil resistance.

In the case of series windings the ampere-turns are not affected by the coil heating, as in the case of a shunt coil, except in so far as the increase of resistance of the winding due to heating may reduce the current flowing in the circuit. This factor need be considered only when the coil resistance is comparable with that of the series circuit.

Chapter V

OPERATION OF ELECTROMAGNETS

THE efficient operation of an electromagnet is dependent upon a variety of factors, determined by the application and the particular conditions of working. Due attention to these factors is essential to the successful use of electromagnets, and in the present chapter we deal with some of the principal matters requiring consideration.

Speed of Operation

In many types of electromagnetic device, the speed of operation is of importance. In the case of contactors and relays, for example, a high speed is usually desired, while in the case of electromagnets operating brakes the speed of response may be of very great importance. The pull exerted by a D.C. electromagnet does not reach its normal value immediately the coil is energised. It would do so if the current in the coil reached its final value at once, but this is prevented by the inductance of the winding, which is always present to an extent depending upon the particulars of the winding and the magnetic circuit. If L is the inductance of the coil in henries, and I the final value of the current as determined by the resistance R of the coil and the applied voltage, the current at time t seconds from the instant of closing the circuit will be given by the well-known formula

$$i = I(1 - e^{-Rt/L})$$

The larger the value of L, the smaller will be the current at a given time, which means that the rise of current will be slower and a longer time will be required from the moment of closing the circuit to the moment when the coil is producing sufficient ampere-turns to operate the electromagnet as shown in Fig. 30. The inductance may thus be regarded as a retarding factor, and its effect is sometimes very marked. With a given magnetic circuit, it is proportional to the number of turns in the coil, so that the retarding effect is greatest with high voltage coils, which necessarily have a large number of turns.

In some cases the rate of release of the electromagnet when disconnected from the supply is also of importance. In the case of a brake, for example, which is usually applied by a spring or weight when the electromagnet is disconnected, the time of release must generally be as short as possible in order to ensure the greatest rapidity of response. Anything in the system which delays the collapse of current in the coil will defeat this object. Most of the various forms of protective circuit, such as discharge resistance and condenser quench circuits have this effect, so that discretion must be used in the application of these arrangements. A further cause of sluggishness is a metal coil bobbin, or in fact any closed metallic circuit embracing the magnetic flux. Such circuits, generally in the form of a metal sleeve over the core or embodied in the coil are often used in cases where it is specially desired to retard the releasing action, but where fast release is required it is necessary to avoid these arrangements.

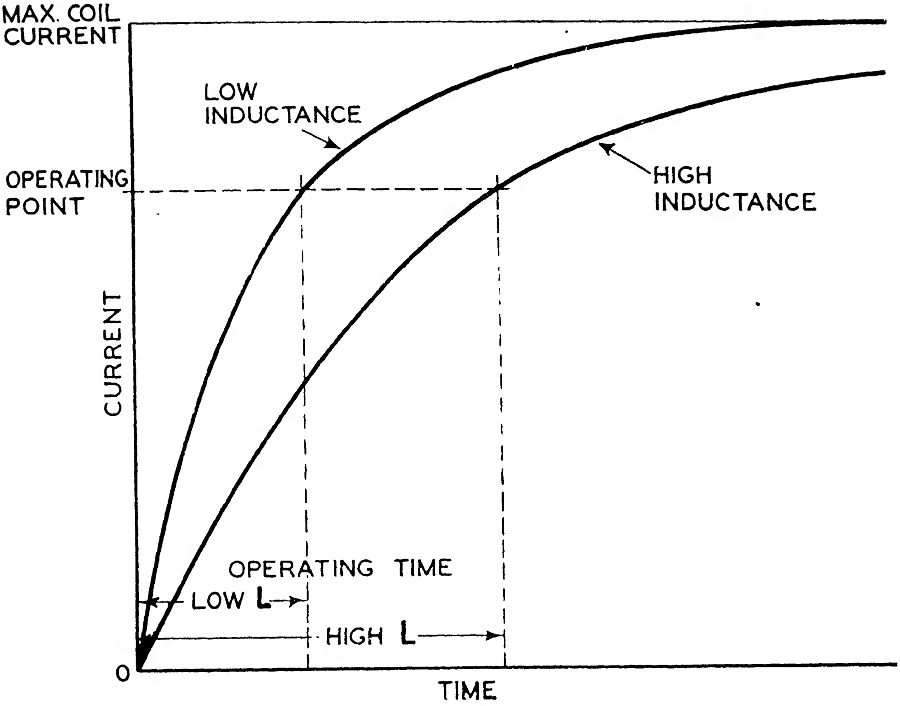

Fig. 30.—EFFECT OF COIL INDUCTANCE ON OPERATING TIME.

Returning again to the switching-in process, it may be noted that by designing the coil for a lower voltage and providing a resistance in series with it we may secure a circuit of lower inductance which will consequently have a faster rate of response. This arrangement is in fact employed in practice in cases where high speed operation is required. Its disadvantage is, of course, that a resistance of some kind must be provided. It must be remembered, however, that in the case of large coils there is an appreciable saving in cost owing to the use of a larger size of wire. The resistance need be rated only for the same duty cycle as the coil, and will thus be small if the duty is intermittent. The circuit conditions with this method of operation are considered on page 73.

A further point which must be considered is the possibility of an electromagnet failing to release when disconnected, owing to residual magnetism. This is not likely to occur with heavily loaded mechanisms, but with light loads it is important that proper measures be taken to prevent it. The usual arrangement is a non-magnetic pin protruding a little distance beyond the plunger or armature in such a way that when the electromagnet has operated there remains a small air gap. The respective surfaces are therefore not in actual contact, and the effect of residual magnetism is overcome. In some cases, as for example relays, where the operation may be very frequent there is a possibility of the pin becoming gradually flattened and worn away to such an extent that its action is lost. In such cases a lamination of suitably hard material such as phosphor-bronze may be placed flat across the pole face, so as to resist better the hammering action. If there is very little mechanical wear, the pole face may be electro-plated so as to give the same effect.

Protection of D.C. Electromagnets

When an inductive circuit, such as the winding of a D.C. electromagnet, is disconnected from the supply the collapsing flux induces in the turns of the winding an e.m.f. which is proportional to the number of turns and the rate at which the flux collapses. It follows that this inductive e.m.f. is generally greater with high voltage windings, owing to the large number of turns, and is also influenced by the rate of disconnection of the circuit. If the circuit is broken at such a high speed that no spark or arc occurs, then disconnection is very sudden, the rate of collapse of flux high, and the induced e.m.f. large. In the case of even medium size electromagnets an inductive e.m.f. of several thousand volts may readily be reached across the coil terminals upon disconnection, and this rise of voltage places a great strain upon the coil insulation, frequently leading to breakdown unless due precautions are taken in the form of protective devices.

It is not possible to formulate exact rules for determining when a protective device is required, owing to the large number of variables which enter into the question. A great deal depends upon the construction of the winding and its insulation. If this is such as to ensure high dielectric strength, a correspondingly high inductive voltage may safely be withstood during repeated switching actions. In the case of large electromagnets, in which a large amount of inductive energy is stored, a protective circuit is usually necessary, especially if the winding is designed for a high voltage and therefore has a large number of turns. In the case of large windings a protective device serves also to protect the contacts of the switching device against the very harmful effects of interrupting a highly inductive circuit.

The most widely used of protective circuits in general practice is the discharge resistor connected permanently across the winding. If this arrangement is impracticable owing to the size of resistor required and the wastage of power in it the alternative is to arrange that the discharge circuit is completed only when, or just before, the main circuit is opened. This arrangement is generally employed in the case of large lifting magnets, for example, in which case the discharge circuit is completed by auxiliary contacts on the control switch when nearing the "off" position or by means of the control contactors when the currents are too large to be handled by a manually operated switch.

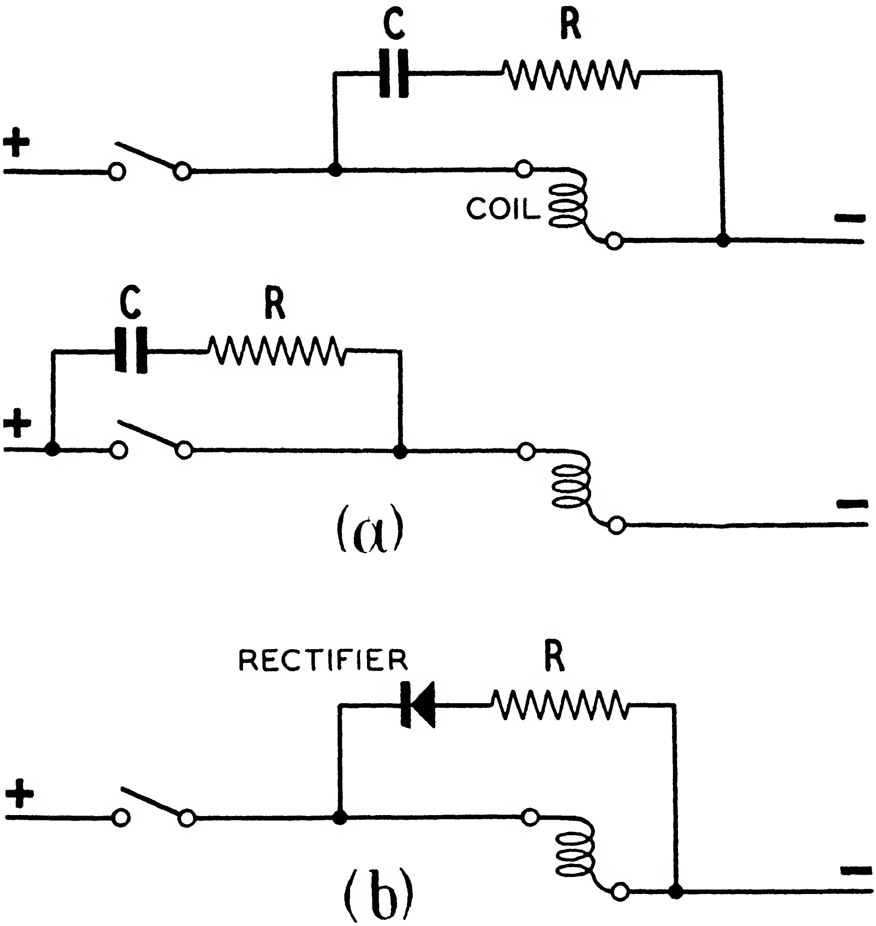

Fig. 31.—Alternative forms of protective circuit.
(*a*) Alternative arrangement of condenser and resistance.
(*b*) Use of rectifier in protective circuit.

The value of resistance required in a given case depends upon how low it is desired to keep the inductive voltage rise, which becomes lower for lower values of resistance. Too low a value, however, will cause an appreciable lag in the rate of fall of current in the winding, and this may be undesirable in some cases, as we have just seen. In practice, a discharge circuit resistance of about twice the resistance of the winding is normal, but fairly wide deviations from this figure are found, according to the particular conditions.

Other types of protective circuit as shown in Fig. 31 include (a) a condenser and resistance in series across either the winding or the switch contacts; and (b) a dry type rectifier (copper-oxide or selenium), usually in series with a resistance, across the load.

The Heating of Windings

The temperature attained by a coil during normal operation must obviously not reach a value which would be harmful to the insulation, so that it is important to be able to predict the temperature-rise under given conditions. The temperature-rise of a coil is—

(a) Proportional to the watts expended in the coil.

(b) Inversely proportional to the area of the cooling surface.

(c) Proportional to the length of time the coil is energised.

(d) Dependent upon the type of surface.

It follows that for a given kind of coil the temperature-rise is proportional to the number of watts per sq. inch of the effective cooling surface.

It must be remembered, however, that the surface has a considerable effect upon the rate at which heat can be radiated, and hence upon the temperature-rise of the coil. A rough surface is a more efficient radiator than a smooth one, and will consequently keep cooler for a definite wattage dissipation.

It should also be borne in mind that the thermal conductivity of the internal coil structure has an important effect upon the transfer of heat from the body of the coil to the radiating surface. This factor is considerably affected by the kind of impregnation used, and in general an impregnated winding will have a much lower internal temperature-rise than one which has not been treated.

Another case in which the temperature-rise is greatly reduced is when the coil is in close contact with a cooling mass. An example is provided by a magnet construction, such as a lifting magnet, which permits of the body being filled with compound after the coil is in position. The heat generated in the coil in such a case is not dissipated at the coil surface, but over the body of the magnet itself. The thermal conductivity of the compound not only results in a larger cooling surface but also increases the thermal capacity by conveying the heat to the magnet body and thus allows the coil to be energised for longer periods before acquiring a given temperature-rise. In a similar manner, the temperature-rise of an air-cooled coil may be reduced by arranging that its ends make effective contact with the magnet body. A coil which is loose in a magnet frame will obviously have a greater temperature-rise than when it is clamped so that some of its heat is conveyed to the frame.

The distribution of temperature in a coil is a matter of considerable importance, and is greatly influenced by the kind of covering on the wire, the way in which the coil is wound, its dimensions and whether or not the coil is impregnated. It is obvious that the best results are obtained when the thermal capacity and thermal conductivity through the winding are high. This requires that the winding shall be closely wound and impregnated with a material of high thermal conductivity. Unimpregnated enamelled wire windings have good properties in this respect, but cotton or silk covered wire when thoroughly impregnated is probably better. It is of course essential that the impregnation should penetrate through the entire winding, as otherwise the unimpregnated portions will constitute overheated regions.

In general practice the surface temperature of a winding, as given by the reading of a thermometer, is taken as the criterion of heating. Considerable care is necessary when measuring the temperature of a coil by means of a thermometer; otherwise the results are not dependable. In B.S.S. No. 587–1935 it is stated that when a thermometer is used to measure the temperature of a surface, such as that of a coil, the bulb shall be surrounded by a single wrapping of tinfoil, having a thickness of not less than 0·001 inch. The foil shall be turned up at the end to form a complete covering for the bulb, which shall then be secured in contact with the surface under test. The exposed part of the wrapped bulb shall be completely covered with a pad of heat-insulating material, without unduly shielding the test surface from normal cooling. It is also pointed out that an alcohol thermometer should be used in preference to a mercury one in places where there is any varying or moving magnetic field, owing to the effects of eddy currents in heating the mercury and causing misleading results.

It is scarcely necessary to point out that measurements of surface temperature may give a very erroneous idea of conditions inside the coil, where overheated regions may exist for the reasons already mentioned. An alternative method, which gives a more accurate idea of internal conditions, is to compute the temperature of the winding from the resulting increase of resistance as compared with some lower temperature. For this calculation we use the formula

$$R = R_0 (1 + kt) \quad . \quad . \quad . \quad . \quad .$$

where R is the "hot resistance" at a temperature t_2, R_0 the "cold resistance" at a temperature t_1, k is the temperature coefficient of resistance (0·0040 for copper) and t is the temperature-rise, given by $t_2 - t_1$. The procedure is firstly to measure the coil resistance R_0 at normal room temperature before the coil is energised. The coil is then switched on and accordingly heats up until a steady temperature is reached, when the heat generated is exactly balanced by the heat radiated. If the "hot resistance" R is now measured, we have sufficient data for calculating the temperature-rise from formula (29) by rearranging the terms as follows:

$$t = \left(\frac{R}{R_o} - 1\right) \Big/ k \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

The temperature-rise calculated in this way should be higher than that obtained by a thermometer on the coil surface, since the inside of the coil, especially deep down, is hotter than the outside. It may also be pointed out that unless surface temperature measurements are made very carefully the results are likely to be very erratic and misleading. There is of course no reason why temperature measurements should be restricted to final steady temperatures. Intermediate temperatures may equally well be measured, unless the coil is heating too rapidly for accurate readings.

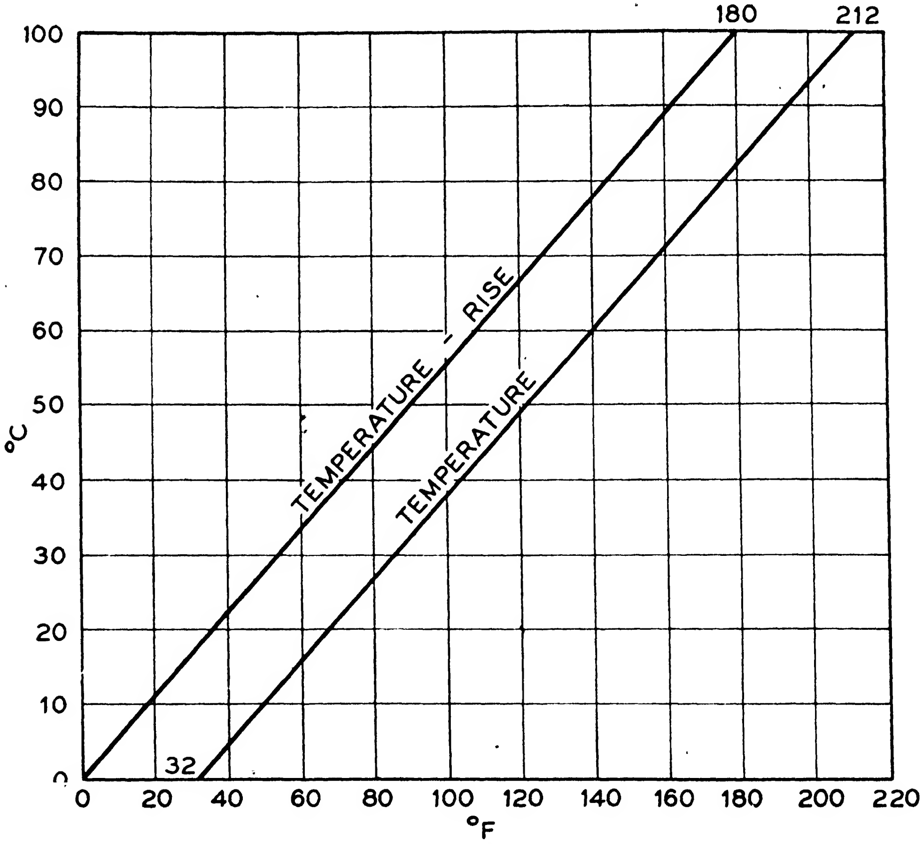

Fig. 32.—Conversion chart for alternative scales of temperature measurement.

Temperatures of windings are usually expressed in Centigrade degrees, but it is sometimes necessary to use the Fahrenheit scale, as for example when only a Fahrenheit thermometer is available. Thus the necessity frequently arises for converting temperatures from one scale to the other. This can be done by means of the usual formulæ:

$$°\text{F.} = °\text{C.}\ 9/5 + 32$$
$$°\text{C.} = (°\text{F.} - 32)\ 5/9$$

It must not be overlooked that in the case of temperature-*rise*, °F. = °C. 9/5 and °C. = °F. 5/9. In order to save calculations, use may be made of the graph in Fig. 32, from which total temperature or temperature-rise may be converted directly from one scale to the other with sufficient accuracy for most purposes.

Calculation of Coil Temperature

Since the temperature-rise of a given coil is proportional to the watts expended and inversely proportional to the area of the cooling surface, we can express the final temperature-rise by the formula

$$T = k\ W/S \qquad . \quad . \quad . \quad . \quad . \ (31)$$

where W and S are the watts and cooling surface respectively and k is a constant depending upon the type of winding. In practice it is rather difficult to decide upon the value of k and the appropriate value of S. So many factors affect the temperature-rise for a given value of W/S that an accurate determination of k can be expected only on the basis of experience with different types of winding. As a guide, it may be said that for plain coils in still air where heat is lost only by radiation and there is no conduction to other material, k may be as high as 200 in the °C. scale, so that a dissipation of 0·5 watt per sq. inch of surface will result in an ultimate temperature-rise of 100°C. Such cases are rarely encountered in practice, and a good average value of k is 120. In cases where conduction and radiation are high, due to extensive contact between coil and magnet frame or forced ventilation, the value of k ranges between 80 and 100. There is a further source of doubt in choosing the value of S, and the question arises whether it should include the areas of the coil ends. This is permissible only if the ends are in effective contact with radiating material, such as the magnet frame, but otherwise they usually contribute little to the loss of heat and it is then best to take the cylindrical surface only.

Although it is often necessary to calculate the final temperature-rise of a coil, there are many occasions when it is desired to know the temperature-rise at a given time from switching on. There are many applications of electromagnets in which the coil is energised only for short periods, and for this class of duty it is important to know the rate of heating with a given wattage or the time for which a given wattage may be dissipated in order to give a specified temperature-rise. The coil heating when cooling takes place follows an exponential law, and the temperature-rise t at a time a seconds after switching on is given by

$$t = T\,(1 - e^{-a/b}), \qquad . \quad . \quad . \quad . \quad . \quad (32)$$

where T is the final steady temperature-rise as calculated from formula (31), e is the base of Naperian logarithms and b is the time in seconds required for the coil to reach the final temperature T if there is no cooling. If then we can calculate the value of b, all the terms on the right-hand side of equation (32) are known, and the temperature-rise of the coil at any time after switching on may be determined. The value of b may be arrived at from the basic formula giving the watts I^2R required to raise the temperature of a mass M grams of a substance with specific heat s through $t°$ C. in a given number of seconds:

$$Mts/\text{time (seconds)} = 0{\cdot}24\ I^2R \qquad . \quad . \quad . \quad (33)$$

Since a cubic inch of copper weighs 0·32 lb. or 144 grams, and the specific heat of copper is 0·095, the number of watts required to raise the temperature of 1 cubic inch of copper through 1°C. in 1 second is

$$\frac{144 \times 1 \times 0{\cdot}095}{1 \times 0{\cdot}24} = 57 \text{ watts} \qquad . \quad . \quad . \quad (34)$$

This calculation assumes that there are no losses, as required by our definition of the factor b, which in the case of a coil is given by

$$b = 57\ VT/I^2R \text{ (seconds)} \qquad . \quad . \quad . \quad . \quad (35)$$

where V is the volume of copper in cubic inches. The application of the foregoing formulæ will be made clear by the following example.

A coil contains 7 lb. of copper wire, absorbs 54 watts and has a cooling surface of 50 sq. inches; It is required to find the time in which the coil will acquire a temperature-rise of 50°C. The final steady temperature-rise can be found from formula (31) taking a value of 120 for k. We then have

$$T = 120 \times 54/50 = 130°\text{C. rise.}$$

From formula (35) we can now find the time required to attain the final temperature-rise T if there were no cooling. It should be noted, however, that for more accurate results we should increase the figure for the weight by say 10 per cent to allow for the thermal capacity of the coil insulation, including impregnation. This will give $W = 7{\cdot}7$ lb., and $V = 7{\cdot}7/0{\cdot}32 = 24$ cubic inches. For the time b, formula (35) now gives

$$b = 57 \times 24 \times 130/54 = 3293 \text{ seconds, or say } 55 \text{ minutes.}$$

The time required for reaching the specified temperature-rise of 50°C. could now be found by solving for a in equation (32), but there is an

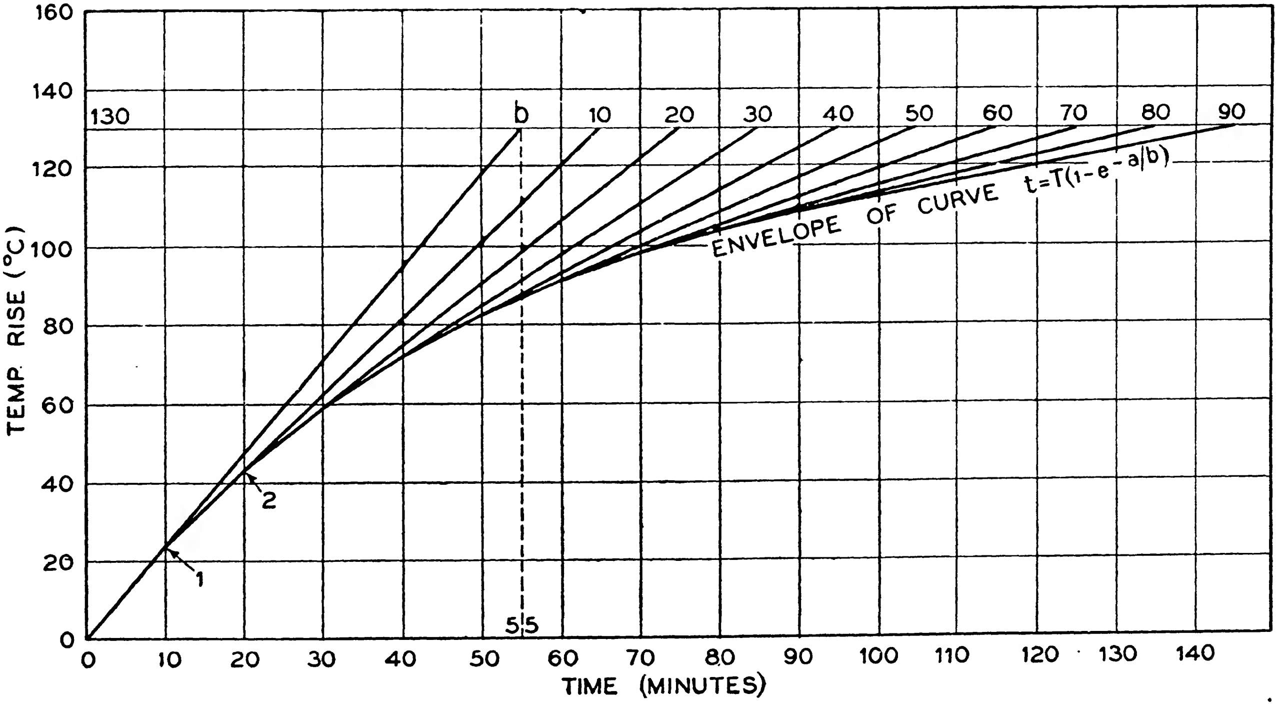

Fig. 33.—Graphical determination of temperature-rise.

alternative graphical method of solution which has the advantage of showing the entire heating curve of the coil. The curve corresponding to the present example is shown in Fig. 33, and is constructed as follows:

The time axis is divided off equally to represent minutes, while temperature-rise is plotted vertically. From the origin a straight line is drawn through the point corresponding to the maximum steady temperature-rise *T* and the time *b* in which this would be reached without cooling. In the present case the values are 130°C. and 55 minutes respectively. To the right from point *b*, new time axis markings are set off, parallel to the original axis and with the same values of sub-division. From the point marked 1 in the diagram, representing the intersection of the line *Ob* with the first time ordinate, another straight line is drawn to the first time ordinate on the upper scale. From point 2, the intersection of this line with the second time ordinate, another line is drawn to the second time ordinate on the upper scale. This process is repeated until the lines so drawn merge into the horizontal line representing the maximum steady temperature-rise, at the same time indicating the shape of the heating curve governed by equation (32). For accuracy, the time divisions should be made as small as convenient. From the curve it will be seen that the time required for the coil to attain a temperature-rise of 50°C. is about 24 minutes. This result may be checked with equation (32) and will be found to be sufficiently accurate for all normal purposes.

From a graph of this kind it is possible to read directly the permissible time-on periods for coils of the same design but with different kinds of wire; the maximum temperature-rises being taken from Table V on page 62. It will be seen that coils wound with enamelled wire (Class A2) or with synthetic resin impregnation (Class D) have a considerably longer permissible time-on period than those using cotton-covered wire, owing to the higher temperature-rise allowable.

It will be understood that the foregoing considerations do not apply to continuously rated coils, in which the final steady temperature-rise *T* must be within the limits corresponding to the particular class of insulation.

Economy Resistances

At this stage we may consider briefly an arrangement having a wide range of application in D.C. electromagnetic devices where the winding remains energised for long periods. This condition normally requires that the coil shall have a sufficiently large cooling surface to keep the temperature below the maximum for the particular class of winding used, but by means of an economy resistance, sometimes called a cut-in resistance, it is possible to employ a much smaller and consequently cheaper coil. The arrangement consists in introducing a resistance into the coil circuit soon after the device has completed its operation and thus reducing coil current, watts and ampere-turns. This is possible without impairing operation, since the ampere-turns required in a magnetic circuit to sustain a given load are much less than during operation, when the air gap is large.

In the case of a solenoid, for example, it is usually possible to arrange for a small auxiliary switch to be opened when the plunger completes its travel, thus inserting into the coil circuit a resistance of suitable value to reduce the wattage of the coil to a safe value for continuous working. In this way it is possible to expend a very high wattage on the coil, and thus obtain a strong pull during the operating movement. The resistance must be suitably rated to carry continuously the current which flows when it is in circuit. The circuit arrangement is shown schematically in Fig. 34, and the formula giving the value of resistance required may be arrived at as follows:

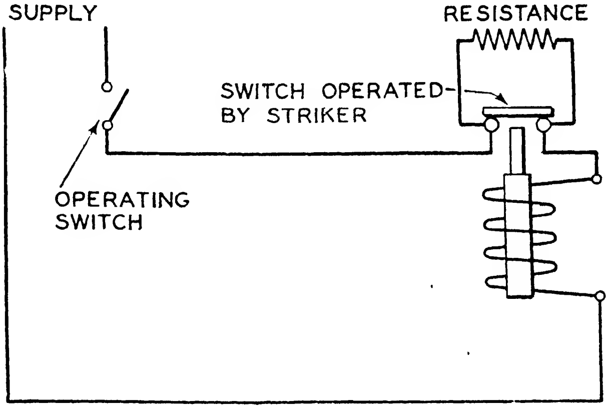

Fig. 34.—ARRANGEMENT FOR AUTOMATICALLY INTRODUCING RESISTANCE INTO COIL CIRCUIT OF SOLENOID.

If I_1 and I_2 are the initial and final currents, they are given by

$$I_1 = E/R_c \text{ and } I_2 = E/(R_c + R),$$

the meaning of the symbols being indicated in the diagram. The wattage absorbed by the coil with the resistance in circuit is evidently $I_2^2R_c$, and this quantity, which we can call W, must obviously not exceed the maximum number of watts which the coil is capable of dissipating continuously without overheating. We have then

$$W = \left(\frac{E}{R_c + R}\right)^2 R_c \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

so that

$$R = E\sqrt{\frac{R_c}{W}} - R_c \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

The resistance used must be capable of carrying the current I_2 continuously.

As an example, we may consider the case of a coil with a resistance of 36 ohms and capable of dissipating continuously 64 watts; the supply being 100 volts. The value of resistance which must be inserted into the coil circuit is, from formula (37)

$$R = 100\sqrt{\frac{36}{64}} - 36 = 39 \text{ ohms},$$

and the accuracy of this result may be checked by working out from formula (36) the coil watts with the resistance in circuit, as follows:

$$W = I R_c = \frac{100 \times 100 \times 36}{75 \times 75} = 64 \text{ watts.}$$

If the coil in question has 1000 turns, the excitation during the stroke will be $I_1T = 2770$ ampere-turns, while at the end of the stroke, when the resistance is in circuit, the excitation will be $I_2T = 1330$ ampere-turns, rather less than half the initial value. A reduction of this order is usually safe, but with excessive reductions there is a possibility of the load being released again when the resistance is inserted. It is of course important that the auxiliary switch inserting the resistance should not open until the latest possible moment during the stroke, since otherwise release may occur before completion of the travel.

Chapter VI

TESTS AND MEASUREMENTS

AS in the case of other electrical equipment, the testing of electromagnetic apparatus is a subject of considerable importance. Adequate testing can reveal faults which would give rise to trouble in practice and also provide valuable data for future design work. We have already seen that successful design depends to a large extent upon information obtained from actual test results.

Testing of insulation and measurement of temperature-rise under operating conditions may be regarded as essential, and there are several other tests which may be necessary from time to time according to circumstances. The order in which the tests are carried out is important and should conform to the general sequence in which they are dealt with below.

Dielectric Test

The objects of this test are: (a) to discover any weakness of insulation which might lead to eventual breakdown; and (b) to ensure that the dielectric provides an adequate factor of safety with the applied voltages likely to be encountered in practice. The test is made by applying a high A.C. voltage between the windings and frame for a given time with the object of straining the dielectric between these parts to an extent considerably greater than it is likely to have to withstand in practice. The test voltage should bear some relationship to the working voltage, and a figure of 1000 volts plus twice the working voltage is generally satisfactory. An alternating voltage at a frequency of 50 cycles is employed, so that the dielectric stress is continually being reversed. The waveform of voltage should be of sine shape, so as to avoid any very steep changes of voltage due to distortion, and also to provide a definite basis of comparison of test voltages. The time of application is usually one minute.

For testing on this basis the apparatus should have means for varying the H.T. voltage, and it will be seen that to cover the normal range of supply voltage a variation from 1000 to 2100 volts will be necessary. There must also be a voltmeter for indicating the H.T. voltage, and suitably insulated electrodes for applying the voltage to the apparatus.

It is a good plan to apply the test before operating the apparatus, so as to reveal any faults in the insulation under cold conditions, and again at the conclusion of tests with the windings at their normal operating temperature. The latter condition approaches more closely to working conditions, and it is sometimes found that the heating of insulation has a profound effect upon its dielectric properties.

The necessity for a test voltage exceeding 1000 volts is sometimes questioned, but in the case of D.C. apparatus in particular the possibility of high inductive voltage rises is so great, and the values are so difficult to estimate accurately, that too much emphasis cannot be placed on the necessity for adequate dielectric tests. In the case of apparatus working on voltages lower than 100, the conditions are of course very different, and the application of test voltages of the order of 1000 volts may be impracticable in some instances. For low voltage apparatus of this kind, reasonable minimum test voltages are about 5 times the working voltage for A.C. and 10 times for D.C. All connections of the apparatus should be complete when the testing is done, so that the test voltage is applied to auxiliary wiring and terminal blocks, etc., as well as the windings.

Insulation Test

This test provides a figure of merit by measuring the actual resistance of the insulation, and is applied between windings and earth as in the dielectric test. The measurement is usually made with a hand-driven ohmmeter of the 500-volt type and the winding may be either cold or hot during the test. It is advisable to take a reading with the apparatus at working temperature, but the test under cold conditions is not important, except as a means of observing the change of insulation resistance brought about by heating of the insulation. In some cases a hot winding will have a much lower insulation resistance than when cold, and the resistance usually regains a high value gradually as the winding cools. This effect is probably due to the liberation of moisture by the heating, and may largely disappear after repeated heating and cooling. Readings of 20 megohms and upwards indicate satisfactory insulation for all normal purposes. Unduly low values indicate a possible risk of breakdown either upon application of the dielectric test or under switching conditions arising in practice, especially in the D.C. case. The aim should always be to secure the highest possible insulation resistance under all temperature conditions. Sometimes the cause of low readings is to be found in poor insulation of auxiliary wiring, etc., in contact with the frame.

Checking of Coil Data

A question which naturally arises in the testing of an electromagnetic device is whether the winding is in accordance with the design data. A check of the coil resistance with the intended value is no criterion, as sometimes a coil is wound to the correct resistance by using more or less turns than specified. If, for example, the correct number of turns is wound and the resistance found to be below the specified value, the correct resistance may be obtained by winding more than the proper number of turns, provided of course that this does not result in the coil being oversize. In such a case there will be more than the required number of ampere-turns, and no overheating, since the watts absorbed by the coil on a given voltage are dependent upon the resistance. If, on the other hand, it is found that the full number of turns cannot be accommodated in the available winding space, the omission of turns will usually result in the resistance also being below the proper figure. The result is two-fold; firstly, the number of ampere-turns may be below the intended value, and secondly, the coil will absorb more than the intended number of watts on a given voltage. Both conditions are very undesirable, and are not necessarily due to faulty winding. They can result also from inaccurate design.

The resistance of a coil can, of course, be measured quite readily by means of any of the usual forms of bridge adapted for this purpose. A high accuracy is necessary, so that there shall be no ambiguity in deciding whether or not the resistance is within satisfactory limits. These limits should in all cases be specified by the design department, and represent a definite tolerance above and below the nominal value. The matter of resistance limits is not so simple as may at first appear, and it may be advisable to draw attention to certain points in this connection.

We may take the case of a coil in which the limits of resistance are fixed at 10 per cent above and below the nominal value. If it is assumed that the correct number of turns is wound in each case, we may consider the relative performance of two coils representing respectively the upper and lower limits of resistance. In the first case, the resistance is 1·1 times the nominal value, and consequently the current is $1/1{\cdot}1 = 0{\cdot}909$ times what it would be with a coil of nominal resistance. The ampere-turns are consequently also 0·909 of the nominal value, so that if we assume a linear relation between flux density and ampere-turns (straight part of B–H curve) the pull obtained will be only $0{\cdot}909^2 = 0{\cdot}826$ of the nominal, because pull is proportional to B^2. The pull is thus about 17 per cent less than would be obtained with the proper value of resistance; a rather large reduction in most cases. The watts will be $0{\cdot}909^2 \times 1{\cdot}1 =$ approximately 90 per cent of nominal, so that there will be less heating. If the coil resistance is 10 per cent low, the current will be $1/{\cdot}9 = 1{\cdot}11$ times the nominal. The ampere-turns will therefore be 1·11 times nominal, and the pull about 1·23 times nominal. It will be seen, however, that the watts are now $1{\cdot}11^2 \times 0{\cdot}9 =$ approximately 1·11 times what they would be with the nominal value of resistance, so that the coil heating will be greater.

These considerations show that it is not permissible to fix an arbitrary limit to coil resistance. The limit must be decided on the basis of the performance under the extremes of the permissible variation of resistance. The limits should naturally be as wide as possible, so as to avoid unnecessary difficulties in winding, and there is no reason why the positive and negative limits should be the same. As we have seen, the upper limit is governed by ampere-turns, and the lower limit by the permissible wattage dissipation.

Another important factor affecting resistance limits is the tolerance of size in manufacture of the wire. On page 53 it is shown that the variation in size of a given gauge may be such that in the case of fine wires the resistance tolerance may be as high as ± 15 per cent. When a wire with this tolerance of variation is used for winding purposes it is obviously impracticable to apply a resistance limit of less than ± 15 per cent to the finished coil. The limit must always be even greater than the tolerance of wire resistance. It will be seen from the figures referred to that a coil resistance can scarcely ever be specified to limits closer than ± 5 per cent, and in the case of wires smaller than about 22 s.w.g. it is necessary to have a greater limit, which may easily exceed 10 per cent, or even 15 per cent for fine wires. Under ordinary commercial conditions of manufacture a tolerance of 10 per cent is generally satisfactory for wires not smaller than about 40 s.w.g.

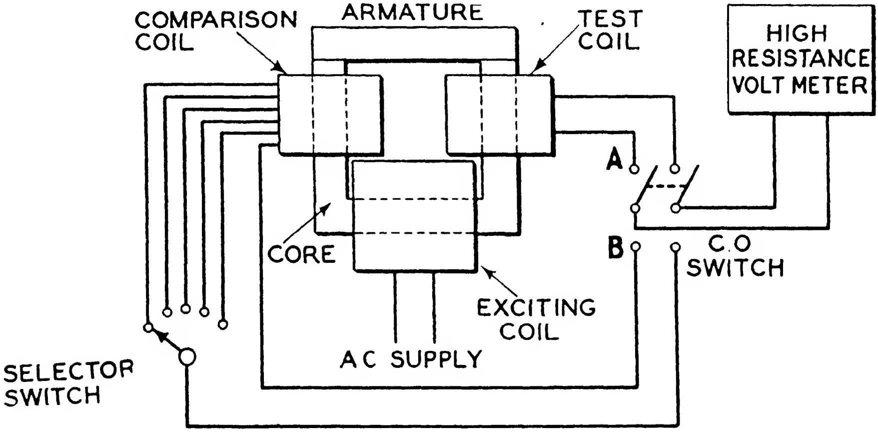

Fig. 35.—CIRCUIT FOR MEASUREMENT OF COIL TURNS.

With regard to the checking of coil turns, the foregoing considerations will make it clear that the measurement of resistance can provide no accurate information of the number of turns in a coil. In cases where it is desired that the number of turns should be accurately measured, use may be made of the circuit shown schematically in Fig. 35. The arrangement consists of a U-shaped laminated core having an exciting coil operating from the A.C. mains and a comparison coil mounted on one limb. This coil is provided with as many tappings as practicable, and has a total number of turns corresponding approximately to the maximum number of turns of the coils to be tested. The tappings are connected to a selector switch, the points of which are marked to indicate the corresponding number of turns selected. The test coil is placed on the other limb of the core, and the magnetic circuit is completed by a hinged or removable armature. A high resistance voltmeter is used to measure the output voltage of either the test coil or the comparison coil, according to the position of the changeover switch. For accurate results it is essential that the voltmeter resistance should be high in relation to the impedances of the windings, and for this reason a thermionic voltmeter is desirable.

The operation of the circuit is as follows: The armature is lifted and the test coil put into position and its leads connected to the appropriate terminals. The exciting coil is then switched on, and the selector switch moved until the reading of the voltmeter with the changeover switch in position A (test coil voltage) is as nearly as possible the same as in position B (comparison coil voltage). The number of turns in the test coil now bears the same relationship to the number of turns in the tapping of the comparison coil as the respective output voltages of these two coils, since both are threaded by the same flux (see formula 17 on page 46). Suppose, for example, that the 500-turn tapping gives the closest equality of readings and that in positions A (test coil) and B (comparison coil) of the changeover switch the voltmeter readings are 55·6 and 67·2 respectively. If these voltages are called E_t and E_c, then

$$E_t/E_c = x/500,$$

where x is the number of turns in the test coil. From this relationship it is seen that

$$x = \frac{500\ E_t}{E_c} = \frac{500 \times 55{\cdot}6}{67{\cdot}2} = 414 \text{ turns approx.}$$

The degree of accuracy obtainable depends of course upon refinements of design and care in making the measurements.

Detection of Short-Circuited Turns

The danger of short-circuits in coils intended for operation on A.C. has already been stressed, and it is very necessary that any short-circuits which may be present in a coil should be detected on test. In the majority of D.C. applications the effects are not important, unless of course the number of turns affected is so large as to upset the winding particulars. In the case of small D.C. relays, however, and especially where high speed operation is required, the retarding effect of short-circuited turns may be very undesirable.

A basic arrangement for detecting the presence of short-circuited turns in a coil winding is shown in Fig. 36. The excitation coil is fixed permanently on one limb of the magnetic core, which can be completed by means of the hinged armature.

In operation, the coil under test is placed upon the second limb, and the armature then placed in position across the limbs. The current in the test coil is recorded by the sensitive ammeter at A. If this current is greater than that recorded when the test coil is not present, there is an indication of a closed circuit in the test coil. Various refinements of this method have been produced, and in some it is arranged that the voltage induced in the test coil is a large multiple of its normal operating voltage, so as to precipitate the failure of any weak points in the coil insulation between turns. It is, of course, necessary that the voltage applied should be kept very constant, as otherwise there will be risk of confusion owing to changes in the excitation current from this cause.

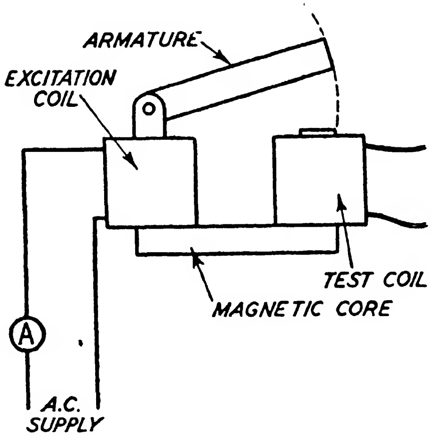

Fig. 36.—SIMPLE ARRANGEMENT FOR DETECTING SHORT-CIRCUITED TURNS IN A COIL.

It may be noticed that this arrangement also provides a means of testing for breaks in the coil winding. If no breaks are present, the ammeter will give a sharply increased reading when the ends of the test coil are touched together or connected to the ends of a resistance.

A more sensitive arrangement is shown in Fig. 37. In this case the laminated core is E-shaped, and carries an exciting coil on the centre limb and two identical balancer coils on the outer limbs. It is also arranged that the coils to be tested can be placed over either of the outer limbs. In operation, the exciting coil is connected to the A.C. supply and the balancer coils B_1, B_2 adjusted so that when connected in opposition the sensitive voltmeter V indicates zero. This adjustment, which may necessitate removal of turns from either balancer coil, is carried out without the test coil and with the armature in position. If the coils are rigidly fixed, this adjustment should be required very infrequently, although the condition should be checked before a test is made. The coil to be tested is slipped over an outer limb as shown, the ends being kept separate, and the armature placed in position. The presence of short-circuited turns in the test coil is immediately made evident by a reading of the voltmeter, caused by a change in the flux distribution between the outer limbs and a consequent disturbance of the balance between the respective voltages of the balancer coils. With a sufficiently sensitive voltmeter, short-circuits of high resistance can be detected with this arrangment. A most important requirement is that the armature should fit well and always in the same position; otherwise the flux distribution will change each time the armature is replaced and consistent results will be impossible. A hinge on one side, free from side play, and carefully fitted surfaces will reduce disturbances from this cause to a minimum.

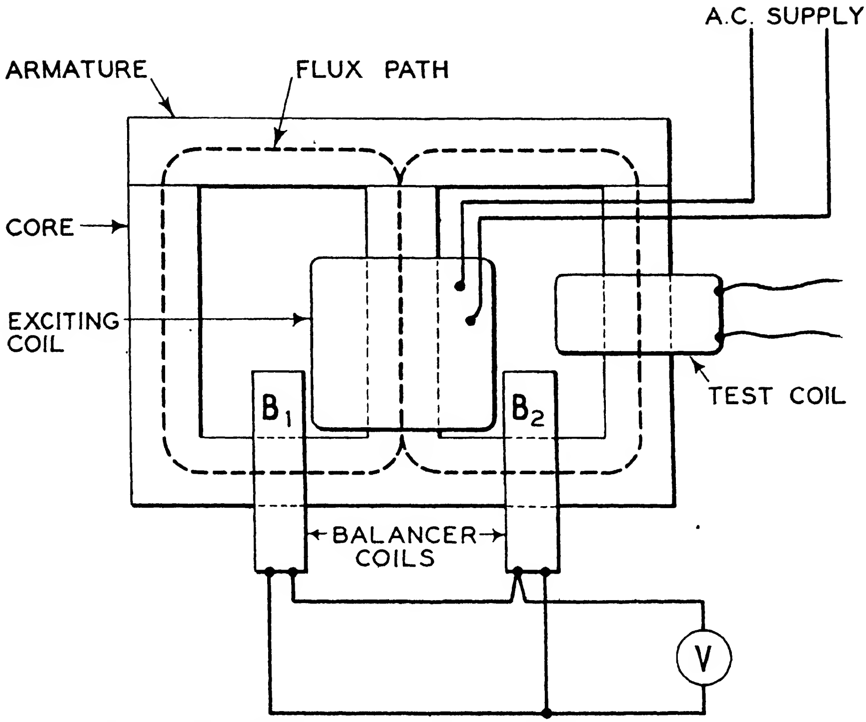

Fig. 37.—SENSITIVE CIRCUIT FOR DETECTION OF SHORT-CIRCUITED TURNS

Impedance and Inductance Measurement

The impedance of an A.C. coil may be determined by measuring the R.M.S. current flowing through it and the R.M.S. voltage across it. If the meter impedances are high enough in the case of the voltmeter, and low enough in the case of the ammeter, to be neglected, then the impedance is given by

$$Z = E/I,$$

where E and I are the voltage and current respectively.

Since the impedance of a coil as determined above is expressed by

$$Z = \sqrt{R^2 + (2\pi fL)^2}$$

and since R may easily be measured, then if the frequency f of the supply is known, the inductance may be calculated from the equation

$$L = \frac{\sqrt{Z^2 - R^2}}{2\pi f}$$

It should be particularly noted that the value of L derived in this way is the inductance of the winding when the A.C. voltage E is applied to its terminals. In general, the inductance will vary according to the value of E.

As an alternative, use may be made of any of the bridge methods of inductance measurement. Suitable bridges are available in various forms, permitting the direct measurement of inductance to a high degree of accuracy.

Temperature Measurement

We have already discussed the relative merits of thermometer versus resistance measurements of temperature (see page 83) and there is little doubt that resistance measurements provide the best criterion. Routine tests of electromagnetic apparatus may require that coil temperatures shall be measured by thermometer for the purpose of comparison with B.S. or other specifications, but for measurements intended to provide data for comparison or design purposes the resistance method has much to recommend it. In any case, it is most important that the method of measurement should be clearly stated, since in a given case the two methods yield rather widely different results. The difference is chiefly noticeable during the early stages of coil heating, when a steep temperature-gradient exists between the inside and surface layers of the coil. A resistance measurement of temperature will then give much higher values than a thermometer measurement made at the coil surface. There is the added consideration that the varying temperature always lags behind the temperature changes, so that thermometer measurement is not suited to the plotting of heating curves. On the other hand, a series of resistance measurements may readily be made during heating, so as to allow of calculation of the corresponding temperature-rises at the points of time corresponding to the successive readings. Heating curves of the form shown in Fig. 33 (page 87), plotted in this way are of the greatest help to the designer. Accurate measurements of final temperature-rise, together with coil surface and the watts dissipation also allow of the evaluation of k in formula (31) on page 85 and thus provide useful information for subsequent estimates of temperature-rise in coils of similar type.

It should be remembered that low temperature-rise is obtained with effective conduction of the heat from the coil as well as unrestricted ventilation, and part of the routine of testing should be to ensure that coils make good thermal contact with their magnet frames. In some cases, all the difference between failure and success in passing a specification of temperature-rise may depend upon due attention to this point.

Adjustments and Test Data

It is obviously impossible to describe here all the adjustments which may be necessary in the wide variety of electromagnetic apparatus used in practice, but attention may be drawn to some basic principles which find extensive application.

In connection with D.C. relays, it is frequently necessary that pick-up and release should take place at definite values of current. The necessary adjustment can be obtained by means of adjustable stops which limit the air gap as shown in Fig. 38. In this case the relay is shown open, and the air gap in this position is limited by the stop *A* which can be adjusted by means of the screw so as to increase or decrease the gap and thus respectively increase or decrease the current at which the armature is attracted. The stop *B* similarly limits the closing travel, and by means of this adjustment the air gap which remains between armature and pole face when the relay is closed can be made large or small. A large gap means a relatively low flux density and reduced pull, so that with falling current the armature is released at a higher current value than it would be if the gap were small. If the armature is allowed to make contact directly with the pole face a much greater pull is developed, and the relay remains closed with much lower values of current. It will be seen from Fig. 38 that the contact springs also affect the release of the relay, since the force which they exert when closed is opposed to the electromagnetic pull. A certain amount of adjustment may consequently be obtained by varying the contact spring pressure, although it must be remembered that this pressure determines the current which may be safely dealt with by the contacts. In some cases, relays are provided with a tension spring, as shown at *C* in Fig. 38, to oppose the closing motion. Such a spring has two functions: firstly, to prevent accidental closing of the relay under the action of tilting or jolting, and secondly, to provide a means of adjusting the values of operating current. In the latter case a tension adjustment is provided.

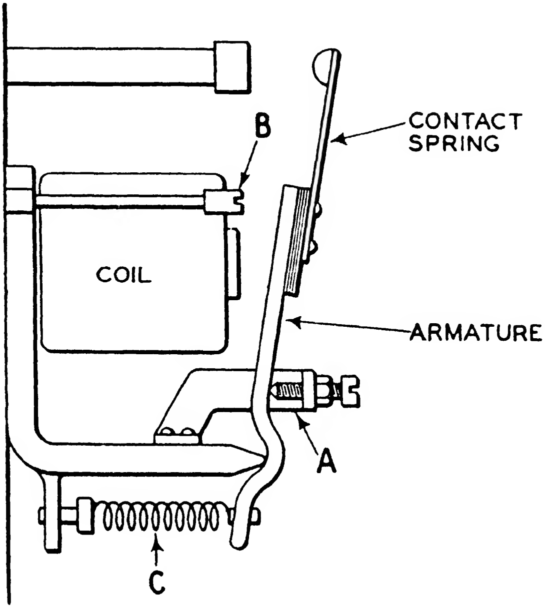

Fig. 38.—Arrangement of adjustments on D.C. relay

The adjustment of relays should be made with the operating coil at normal working temperature. This applies especially to voltage relays, in which case the increase of resistance due to the heating of the coil changes the value of voltage required to produce a given number of ampere-turns. For this reason, the calibration of a voltage relay with a cold coil will in general be appreciably different from the calibration of the same relay at working temperature.

In the case of solenoids, it is necessary that the specified pull shall be checked at the proper stroke with the coil at final working temperature and with a voltage of 80 per cent of the nominal value in the case of D.C. and 85 per cent in the case of A.C., unless otherwise specified. When it is stated that a solenoid is required to lift a certain number of pounds through a certain stroke it is evident that this pull is exclusive of the weight of the plunger, and represents the weight which is attached to the plunger when the latter is complete with its means for attachment to the load. In some cases the weight of the plunger is of interest in connection with the service for which the solenoid is intended, and its value should be recorded in the test data.

Solenoids of representative design should be tested to determine the pull at various strokes. Curves should be made to show the pull-stroke characteristics with the coil at normal operating temperature, both at rated voltage and at an agreed percentage of rated voltage; the latter test being carried out after the normal temperature-rise corresponding to full voltage operation has been attained. This procedure ensures that the solenoid will be able to perform the required work under all normal conditions of service.

In the case of solenoids, or other electromagnets, intended for intermittent service, it is important that testing should be carried out with the appropriate duty cycle. It is a relatively simple matter to arrange a motor-driven contacting device to energise the operating coil for the required periods and leave suitable rest periods. It may be specified, for example, that the electromagnet is to be on for 2 minutes in every 5 minutes, in which case heating considerations may allow the use of a smaller frame size than would be required to exert the specified pull continuously. In such a case the relation between temperature-rise and time will be as shown in Fig. 39. During the first 2 minutes of the "on" period the the temperature-rise reaches point *a* of the heating curve. At this point the coil is de-energised, and begins to cool; the temperature-rise dropping to point *b* during the 3 minute cooling period. The curve *ab* has the same slope and shape as the portion a_1b_1 of the cooling curve parallel to it. At point *b* the coil is switched on again, and reaches the temperature-rise corresponding to point *c* in the following 2 minutes; curve *bc* being parallel to portion b_2c_1 of the heating curve. As this cycle of operations continues, the peaks of temperature-rise increase until eventually they remain at the same value. This value must be below the maximum specified temperature-rise for the particular class of winding. When this condition has been reached, the resistance of the winding is at the maximum value it will reach under the prescribed duty cycle, provided that the cycle is continued long enough, and the pull with a given applied voltage is consequently a

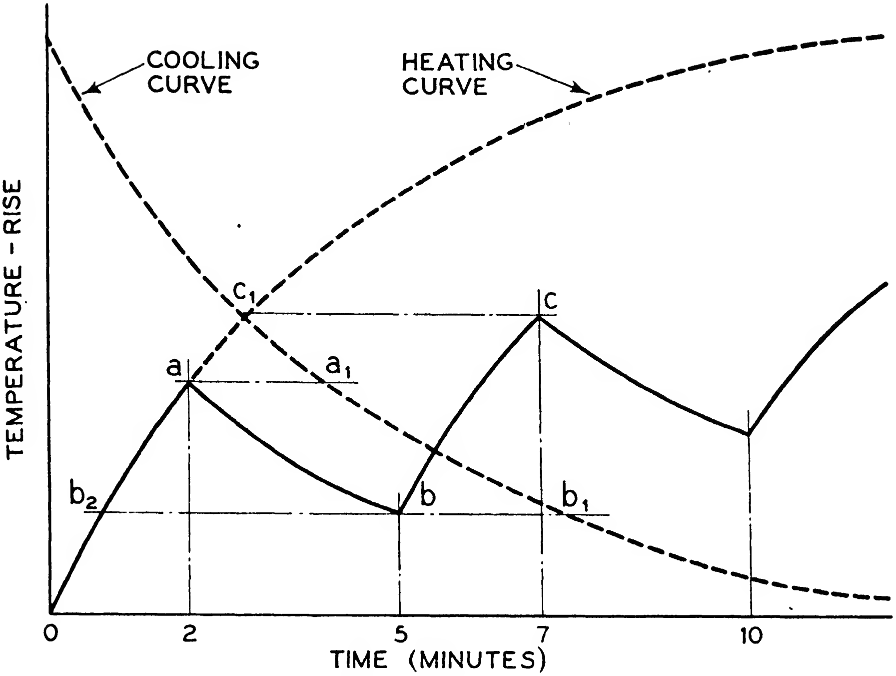

Fig. 39.—Heating of winding on intermittent duty cycle.

minimum. This is the condition in which the electromagnet should be tested to confirm that it will perform the required duty.

Adjustment of A.C. Apparatus

In the case of A.C. electromagnets it is necessary to ensure that the laminations of core and plunger or armature are tightly clamped or riveted, as the case may be. Where clamps are employed, the bolts should have shakeproof nuts, as otherwise they are likely to become loose under service conditions. Loose laminations are a source of considerable noise in operation due to the A.C. hum.

A further source of noise is the chatter caused by an armature or plunger face which does not sit squarely on the pole face. This condition also causes the exciting current of the electromagnet to be greater than necessary, and therefore causes unnecessary heating of the windings. It may be eliminated by careful facing of the surfaces until they make contact over as large an area as possible. A good plan is to introduce a piece of thin paper between the surfaces and then operate the electromagnet two or three times so as to obtain on the paper an imprint of the area or regions over which contact takes place. These regions are then carefully filed down until the largest possible area of contact is shown when the test is repeated. A primary requirement is that the surfaces should be so located with respect to each other that the region of contact does not vary. A well designed A.C. electromagnet produces very little hum or chatter if due attention is given to the foregoing points.

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