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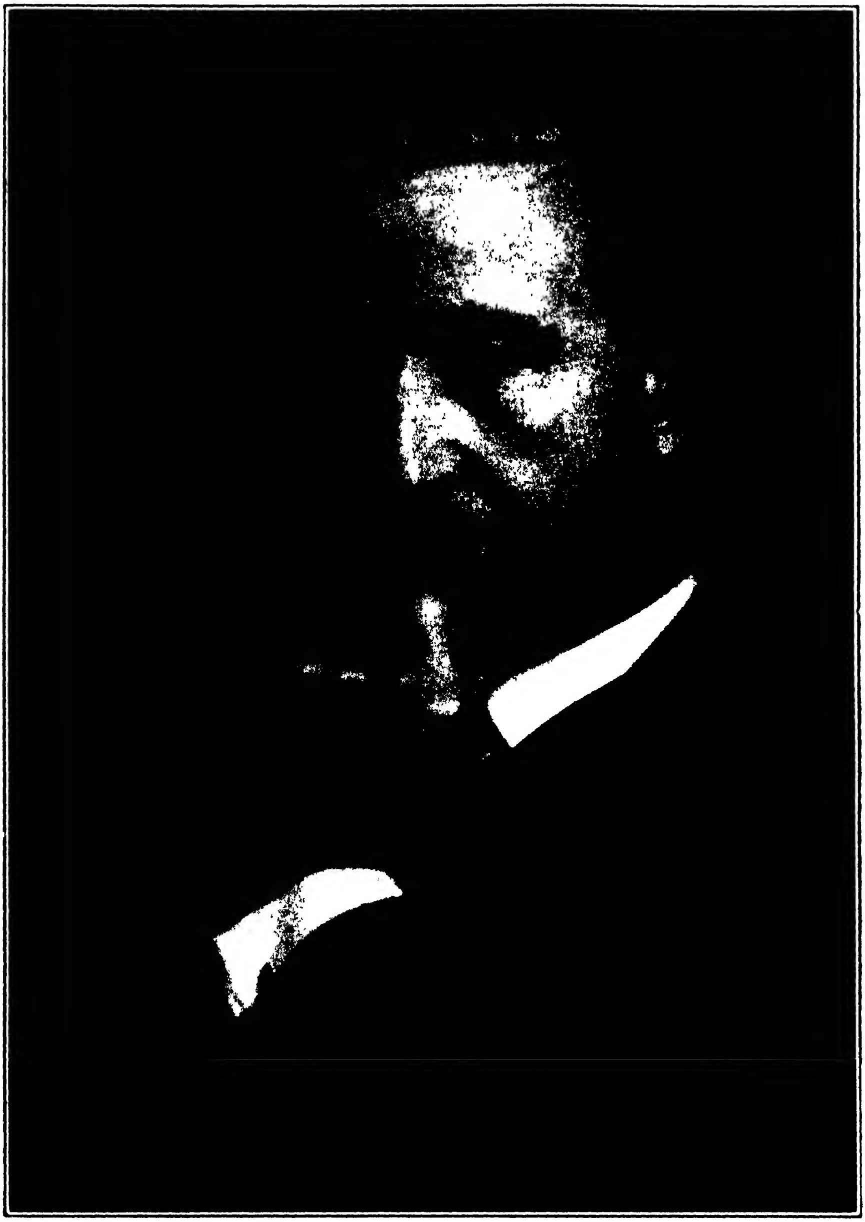

THE AUTHOR.

DISTRIBUTION OF ELECTRICITY BY OVERHEAD LINES.

BY

WILLIAM T. TAYLOR,
M.Inst.C.E., M.I.E.E., Fellow Amer.I.E.E., &c.

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PREFACE.

Having spent a lifetime in the erection, maintenance, and supervision of some of the largest electrical power and lighting undertakings in the world, the author ventured to think that his experience might be of value to this country at the present juncture. The reception of his work *Overhead Electrical Power Transmission Engineering*, issued last year, has more than justified this belief. As a corollary, *Distribution of Electricity by Overhead Lines* is now offered to those who stand in need of what is essentially the latest, best, and broadest of practical experience. Practice, in this country, has hitherto been on a comparatively small scale, and in the present great endeavour to put the country at least on a par with other countries in respect of overhead electrical power and lighting development and practices, it is essential that full use be made of the successes (and failures) of others. Hence, this book is intended for engineers and others engaged in the planning, construction, and operation of overhead distribution lines; and in the text are outlined practical and essential methods for design, construction, operation and protection. A *novel* line distribution system is proposed, the interpretation of which sets forth a discussion of methods emphasizing many advantages of the earthed neutral system and its inherent protection from over-voltages, etc.

To dwell almost exclusively on a knowledge of engineering mathematics will not lead the student very far. Certainly the best preparation is the acquisition of necessary fundamentals, but this, without practice, is almost useless and obviously cannot produce a fully qualified engineer. Hence, there is no need to stress the importance of a knowledge of general overhead distribution *practice* as covered herein.

Some loadings are based on the new 1928 standards, but the book is written *for universal practice* and use; it also contains many tables based on American standards. The practice presented is for all countries; that is to say, the text is not based on any particular set of safety construction standards for this or any other country. The text lays down sound practices based on common-sense methods, reliable in principle, and backed by long and varied experience. The practices mentioned should be as widely used in U.S.A., in Australia, Canada, New Zealand, etc. as in this country, or more so.

The most suitable primary voltage, system, and line, as well as the most suitable secondary system distribution, depend on many diverse conditions. Distribution lines may follow public highways or run across open fields or back-plots; be single-circuit and of single-pole construction, or multi-circuit on structures or frames with joint use of communication circuits; the distribution may be single-phase or polyphase, or both; and, the network may be simple or complex. There are two general conditions to be met at the initial stage: one is the choice of the best system and line, then its building and operation. The author has endeavoured to show which is the best system and line, and how to get the best out of them. The second important step is to make the system and line the most efficient and profitable; the author has also shown the way to achieve this.

Throughout the whole book there is an entire absence of the descriptive matter found in manufacturers' publications and catalogues; also, the endeavour has been to keep clear of assumptions and probabilities, so commonly used. It is obvious that, to complete the economic characteristics, certain assumptions must be made; for instance, one of the many uncertain distribution problems is the inclusion of growth of load in both time-period and amount. For a secondary network in particular, due to the variable and uncertain nature of many of the factors that enter into the calculation of all the economic characteristics, it is not possible to reduce economical design to terms of absolute correct values, and in applying values for the different assumptions to be made, the best that can be done is to apply sound general principles and good judgment based on practical experience.

By the courtesy of Messrs W. T. Henley's Telegraph Works Co., Ltd., photographs appear representing overhead line practice of this country. For such kindly help the author expresses thanks. He hopes also that this endeavour to present the latest results of actual experience in electricity distribution practice may prove of real service to all those engaged in the planning, design, construction, and operation of overhead distribution systems in this and other countries.

WILLIAM T. TAYLOR.

London,
April 1928.

CONTENTS.

POSITION OF FOLDER.

DISTRIBUTION OF ELECTRICITY BY OVERHEAD LINES.

CHAPTER I.

DISTRIBUTION SYSTEMS AND DEVELOPMENT.

Early practical history of a.c. and d.c., more particularly the former, provides interesting reading for every electrical engineer, and the knowledge of methods and systems now available in highly reliable economic and efficient form are of still greater interest and importance. The ultimate system of distribution, which the author has had in mind while writing the text-matter, is the three-phase 4-wire system; this system is more economical where the loads are denser, feeder loads heavier, and distances to outlying districts are greater, all of which meet more correctly the needs of modern requirements.

As we get further away from congested areas so we are forced to eliminate underground service for overhead construction, and incidentally, we reach a stage where, generally speaking, service from direct current is not so satisfactory. At the present time in this country's electrical history we are at a stage where direct-current service is limited to its present extent and/or to be supplanted by alternating-current (a.c.) service, since (for several very important reasons) the latter is more easily adaptable to increases in load and expansion, transmission distance, and so forth.

Taken as an approximate mean, the cost of overhead distribution should not be more than 20 to 30 per cent., and for much rural construction service around 15 to 20 per cent. of that required for underground distribution construction. With existing safety construction standards this figure is very much higher for this country (nearly three times higher) than for most countries. In general, the cost per kVA of overhead distribution line decreases as the voltage is increased; the cost of transformers increases with an increase in voltage. Each case is different, and the cost will depend on distance, size of transformer installations, etc.

For branch lines, single-phase taps for rural areas will, because of cheaper initial cost and the relatively small-sized power installations, be general. Multiple earthing of the neutral on the primary and the secondary distribution is the best practice. Line-construction standards for this country are sure to be modified to permit development of rural areas as well as to permit better line-operating conditions. Means to this end and to reliable construction practice are set forth in the text-matter.

THE interaction of the waves of electricity sent off from both primary and secondary coils was disclosed in M. Faraday's paper in the *Philosophical Magazine* in 1831; this was eight years after the publication of Ampère's *Théorie des Phénomenes Electrodynamique.* In 1834 Michael Faraday discovered the phenomena of self-induction, and Joseph Henry's investigations on induction in general covered the period of 1832–40. The final mathematical formulation of the law of mutual induction is due to F. Neumann (1845).

Gaulard and Gibbs gave the first practical scheme for alternating current distribution from high-pressure to low-pressure, but the first a.c. system was not installed until 1886, and a wide use was not made of the a.c. system until about 1888.

Commencing from about 1893, practically all installations in the U.S.A. were planned and erected on an a.c. basis, one of the early claims being that it had a wider scope of usefulness than the d.c. system, since one could generate at a low safe voltage and, when desired, increase the voltage to almost any practical value with perfect safety, and reduce it to any voltage at the end where required. In 1891 the first 10,000 volt transformers were put into operation; this was in California.

So far back as 1893 both lamps and motors were run from the same circuit, and experience proved that while a slight variation of pressure on the motors would not cause any particular trouble, the successful operation of lamps required a practically constant pressure. About this period the three-phase 4-wire system of *distribution* came into use, and supplied both lamps and motors from one circuit with an economy and success comparable to that of any system; and the *transmission* of power by the three-phase 3-wire system gave all that was desired for safety and simplicity. Some of the earliest a.c. systems in operation up to 1894 were:

Location.	System Used.	Line Voltage Used.
Brescia	Single-phase	15,000
Sacramento, California	Three-phase	11,000
Fresno, California	Three-phase	10,000
Salt Lake City, Utah	Three-phase	10,000
San Francisco, California	Single-phase	8,000
Geneva, Switzerland	Single-phase	6,600
Portland, Oregon	Three-phase	6,000
Rome, Italy	Single-phase	6,000
Lowell, Massachusetts	Three-phase	5,500
Quebec, Canada	Two-phase	5,000
Lauffen-Heilbroun	Three-phase	5,000
Davos, Switzerland	Single-phase	3,660
Telluride, Colorado	Single-phase	3,000
Lauffen-Frankfort[1]	Three-phase	30,000

[1] Experimental; 12,000 volts for 110 H.P. delivered.

The a.c. system has therefore given us, through the use of the transformer (see fig. 1), the utmost facility for using high pressure without fear of it entering the consumer's premises; all this was well known and appreciated in those days. The a.c. transformer and its systems have also lent themselves to accurate distribution by means of induction regulators located at the source of supply; these were then of crude design and construction, and were placed on the back of the switchboard panels in those earlier days. Up to about 1890 there existed some doubt as to whether sub-stations could be made perfectly self-regulating, and it was generally thought that "we might look with favour on adopting sub-stations in the immediate future." So far back as 1886, inventors were engaged in the production of a practical a.c. single-phase motor.

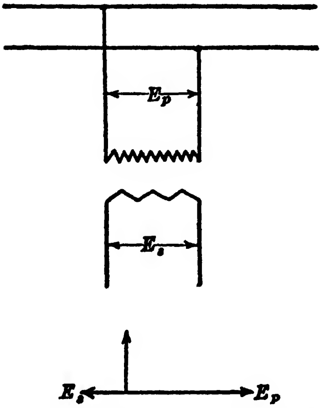

FIG. 1.—Single-phase transformation system from a high pressure to a low pressure.

For about ten years, commencing from around 1893, there existed a certain amount of controversy as to whether the two-phase system or the three-phase system of distribution was best. From time to time opinions were voiced showing the advantages of one polyphase system over the other polyphase system. For more than a quarter of a century the installation of new two-phase systems practically ceased, although it was known at the time that the two-phase 5-wire system of distribution is more economical in copper, etc. (see Table XIV.). In the U.S.A. and other countries a licenced electricity area was not allowed to be monopolised, *i.e.* more than one undertaking could supply electrical energy in the same area. In some cities one company operated a three-phase system of distribution, while another company operated a two-

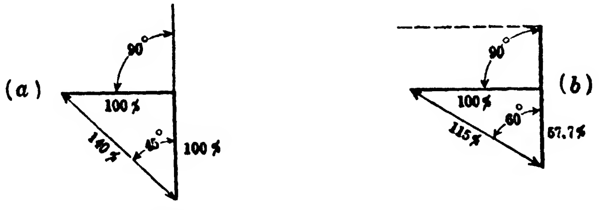

FIG. 2.—Early two-phase and/or three-phase system practised before the "Scott" connection was patented.

phase system in the same city. After a time one company absorbed the other. They then sought for a system for operating both polyphase systems over one circuit. At that time the author was engaged in the operation of a three-phase 4-wire system of distribution for a city also supplied by a competing company operating a two-phase system of distribution, and, in order to get more customers, whether two-phase or three-phase, the author was led to study and develop a method for operating existing two-phase and three-phase motor installations on a united single 4-wire circuit. Afterwards, when both companies came under one control (which they did in 1904), many savings were effected in the dismantling of transformers, existing circuits, and pole lines; in fact a general clean up and saving was made, due to operating two-phase and three-phase motors on one circuit. These early experiences (in every case with overhead lines) helped to pave the way for a wider use of the three-phase 4-wire system of distribution, *i.e.* combined light and power circuit, and to show that it is more flexible and the most desirable system for extensive areas.

The peculiarity of a.c. electric systems, in which currents of one number of phases are changed into currents of another number of phases, lies in the method and means for effecting the transformation. Each portion of the system with its given number of phases is precisely the same and operates in the same way as if the system were of that number of phases throughout. For instance, if three-phase currents are generated and supplied to apparatus from which two-phase currents are obtained and utilised, the three-phase portion of the system behaves like any three-phase system, and the two-phase portion behaves like any two-phase system.

On 14th August 1888, Mr O. B. Shallenberger obtained a patent for a method of obtaining two-phase currents differing in phase from a single-phase circuit. On 7th July 1891, M. von Dolivo-Dobrowolsky patented a system in which he claimed ". . . transformation from a polyphase current of one number of phases to a polyphase current of another number of phases. . . ." It was in 1891 that Dobrowolsky presented a large number of dispositions of apparatus by which polyphase currents of one number of phases are transformed into polyphase currents of another number of phases. This early system of transformation and claim of Dobrowolsky's covers many phase relations, including those commercially used at the present time, known as *Arnold*, *Scott*, *Shallenberger*, *Steinmetz*, *Tesla*, *Taylor*, etc.

Shallenberger disclosed one method in 1888, and the same year

(8th September 1888) he brought out another method clearly describing the application of resultant voltages, and he produced from two-phase currents a resultant phase, *i.e.* three-phase to two-phase or *vice versa.*

It is interesting to review the patent history of the Scott *versus* Steinmetz three-phase to two-phase system, shown in vector diagram (*b*) of fig. 4. In the year 1894 a patent was granted to Mr Charles F. Scott for the "T" three-phase to two-phase transformation—using two transformers. Prior to this date (in 1892) Messrs Hutin & Le Blanc had obtained a patent on a similar method. Not many years passed before Dr C. P. Steinmetz came along with claims on which Scott obtained his patent. An interference was instituted and priority was granted to each in turn (to Scott and to Steinmetz). The examiner of interferences afterwards granted priority to Scott. On appeal, the Board of Examiners-in-chief awarded priority of the issue in interference to Hutin & Le Blanc, while on a further appeal the Commissioner of Patents reversed the decision of the Board of Examiners-in-chief and awarded the priority to Steinmetz. The other parties appealed to the Court. By that time, the patent interests of the two large and well-known interested companies had been the subject of agreement and were then practically identical. During this same year the Hutin & Le Blanc interests and patents were contracted for and controlled by one of the said companies, which need not be mentioned here. The three had come under a single control and they immediately ceased to contest. The appeals were withdrawn and a decision by the Court was thereby avoided. A patent was then issued to Steinmetz after the Scott patent, on the Steinmetz *claims*, was twelve years old.

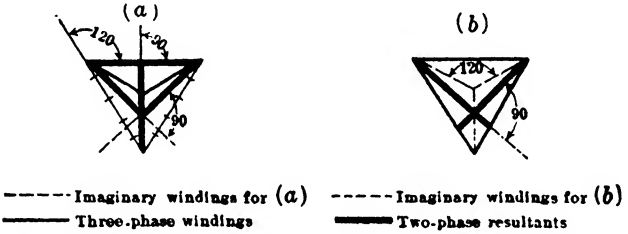

FIG. 3.—Showing similarity of Scott connection (*a*) and Scott *versus* Steinmetz (*a*), and (*b*) the Arnold scheme.

On 14th December 1893 Mr Nikola Tesla obtained a patent on *a method*—that is, the production of a two-phase system from an initial single-phase current. On 27th January 1891 a patent was issued to Tesla on the same line of invention, while on 3rd December 1889 another patent was issued to Tesla in which it was shown how currents of different phases can be obtained.

In fig. 4 (*a*) is shown the ordinary "T" or Scott connection and two others as represented by Steinmetz in his patent case against Scott. In reality each system or method has its particular distinction, that is:

(*a*) Consists of two single-phase transformers of equal ratios, or one differing in ratio approximately 13 per cent. from the other. The main transformer, which is always the one having the 100 per cent. ratio, has a centre tap provided to which the extreme end of the other transformer is connected.

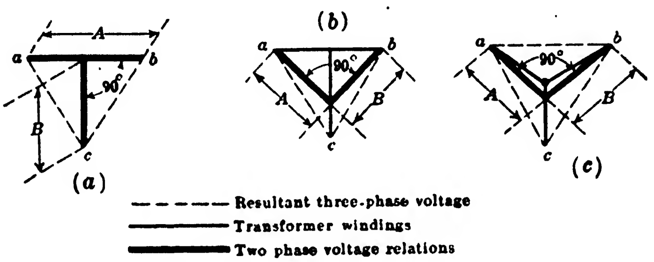

FIG. 4.—Showing three different schemes for two-phase to three-phase transformation; (*a*) = known as the Scott method, using two single-phase transformers; (*b*) = Steinmetz method, using two single-phase transformers—in this method we obtain two distinct two-phase relations; (*c*) = Steinmetz method, using three single-phase transformers.

Note.—An extension of the broken lines of the two-phase relations connects to the sides of a delta.

Applying three-phase currents to the three remaining ends of these two transformers—that is, impressing three single-phase currents each differing by 120 degrees—two-phase currents are obtained from the secondaries.

(*b*) This consists in using the same transformers and the same centre of connection; in fact, it is identical with *a*, so far as it goes, but it extends beyond *a*. A difference exists to such an extent as to make the method employed distinct from either *a* or *c* of fig. 3. The distinctions are fourfold, namely, (1) provision for a special connection on the supplementary transformer in order to obtain the desired two-phase balanced relations; (2) the two-phase relations are resultants and are out of phase with those of *a*; (3) the two-phase resultant voltages are much less; and (4) the two-phase secondary is a three-wire.

(*c*) This method is distinct from *a* and *b* in that a different transformer is required to handle correctly the two-phase resultants, and if three single-phase transformers are provided, they may be of the ordinary design, but a special tap is necessary for at least one transformer.

According to method *a* of fig. 3, the transformer windings are connected in star, while those of *b* are delta connected, but the voltages of the corresponding phases for *a* and *b* are in phase with each other, *b* having a greater two-phase voltage than *a*.

Fig. 3 (*a*) and (*b*) are to be classed as coming under the heading of two-phase to three-phase transformation with three transformers.

Fig. 5 (*b*), patented by the author in 1907, shows another method of transforming phases with three transformers. In this method the magnetic fluxes are not modified, but they remain exactly the same as if each transformer were operating on a single-phase circuit, receiving a single-phase current in the primary and giving out a single-phase current in the secondary. A single polyphase unit or three single-phase transformers may be employed, the respective primaries and secondaries having common magnetic circuits.

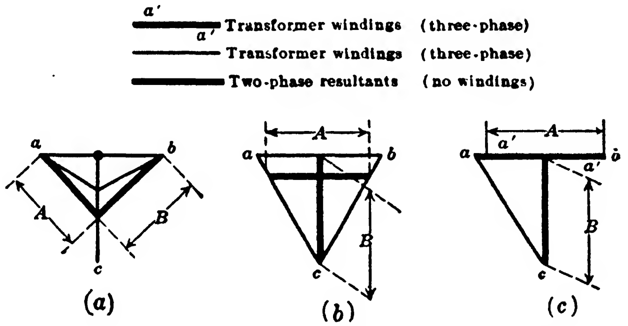

FIG. 5.—Showing three different schemes for two-phase three-phase transformations: (*a*) = Steinmetz two-transformer method, which is the Scott method complete as well as another set of two-phase resultants indicated by thick black lines; (*b*) = Taylor method, using one three-phase transformer or three single-phase transformers; (*c*) = Taylor method, using two single-phase transformers.

The essence of the method employed here is that it requires no modification of the action of the transformers used. In the three-phase system of supply the e.m.fs. of the primary coils differ by the same number of degrees, there being no modification of the phase relations of the two sets of e.m.fs. when the three single-phase transformers, or the three-phase unit, are connected to give two-phase currents in two pairs of conductors joined to approximate selected points of the secondary coils. In other words, this method can be based on the fact that the currents and e.m.fs. differing in phase relation are compounded in exactly the same way that mechanical forces differing in direction are compounded, there being in each case a resultant depending upon the magnitude and relation of the forces that are involved.

From the practical viewpoint, the above described methods [1] of two-phase to three-phase (or *vice versa*) are:

(1) "T," or *Scott*, Method. Using two ordinary single-phase or one ordinary and one special transformer connected in "T," but in no other way.

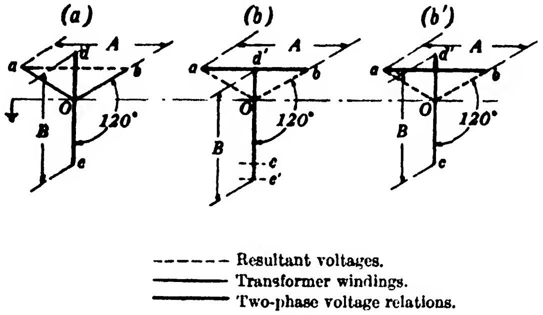

FIG. 5*a*.—Showing two different schemes for symmetrical three-phase or/and two-phase transformation or direct supply, with common return: (*a*) Taylor three-transformer method using a connection such as to obtain for the two-phase one resultant from two phase-windings and one equivalent voltage *cd* from another phase-winding, with common neutral for both systems; (*b*), (*b'*) Taylor two-transformer method, using two single-phase transformers with tap *o* at neutral point so as to obtain balanced three-phase voltages, symmetrical for both systems and using a common neutral point for both systems.

Note.—(*a*), (*b*), and (*b'*) should be useful for the three-phase 3- or 4-wire and the two-phase 4- or 5-wire *interconnected* system; for (*a*) and (*b'*) *cd* equals *ab*, and 01, 02, and 03 are all of equal voltage.

(2) "T," or *Steinmetz*, Method. Using two ordinary single-phase transformers, or one ordinary and one special transformer; and

(3) "Y," or *Steinmetz*, Method. Using three ordinary single-phase transformers, or one ordinary and two special transformers; never connected in delta.

---

[1] Fig. 4 (*a*) method was patented by Mr Charles F. Scott in 1894.

Fig. 5 (*a*) method, which is a combination of fig. 4 (*b*) and (*c*), was patented by Dr Charles P. Steinmetz in 1907, but the application had been filed in the Patent Office for a number of years previous to this date.

Fig. 5 (*b*) and (*c*) methods were patented by the author in 1907. The Pittsburgh Transformer Company, Pittsburgh, Pa., acquired the patents in 1907; this system is used in various parts of North America in cities where 2- and 3-phase systems operate. See *The Electric Journal*, vol. 23, p. 341, July 1926. Also see *Electrical World*, vol. 62, p. 590, 20th September 1913.

(4) "Delta," or *Taylor*, Method. Using ordinary three-phase unit or three single-phase transformers with similar taps on each phase-winding; and

(5) "V," or *Taylor*, Method. Using two of the single-phase transformers mentioned in (4), in case of a burn-out of a phase-winding.

(6) *Taylor* Method. Using one polyphase or three ordinary single-phase transformers, or two single-phase and one special transformer (*od*); never connected delta or the ordinary star.

(7) *Taylor* Method. Using two ordinary single-phase transformers connected at *d′*, and having tap as shown at *o* for neutral, connecting *o a*, *o b*, and *o c* for "Y" three-phase and *a b*, *c d* for two-phase; symmetrical voltage relations and one common neutral return for both systems (as for (6)).

As regards the practical use of (1), (2), and (3), when any one unit or phase-winding of the group becomes disabled, it is impossible to operate and deliver polyphase currents as can be done by method (4), which has the advantage of delivering three-phase and two-phase currents when any one unit or phase-winding becomes disabled; this is accomplished by dropping back to the open-delta or "V" connection, as shown at (*c*) in fig. 5.

At the present time there is great need for economical and reasonably safe standards in overhead electric power-line construction, and this need is growing every year. For rural lines it is, generally speaking, chiefly a matter of initial cost; for main power lines the chief factor is reliability, for the reason that, apart from danger hazards, a breakdown may involve the industries, etc. of a whole town.

The present state of the art (attained elsewhere in overhead distribution for light, heat, and power) has resulted largely from adopting wise standards of safety and construction. In this country at the present day there are problems of the greatest importance which must be faced in order to afford much improved facilities, and so forth, for satisfactory development, such as:

Wayleave facilities, etc.
Post Office (P.M.G.) requirements in general to be relaxed.
Overhead clearances of conductors and wires to be reduced.
Limits of voltage regulation to be increased.
Grading of overhead construction in general to be changed.
Earthing methods and limitation of leakage currents, etc. to be modified.

The easement of one and all these factors must eventually bring about the desired economy and development, which cannot otherwise be attained.

At this stage of the country's rural development there is no necessity to review past history showing the reasons, and why there has always been serious opposition to the use of overhead lines; neither is it necessary to discuss the various suitable grades of *safe* construction and standards. The object of this book is rather to discuss certain accepted good practice, of many years' standing, and working under climatic conditions much more severe than those found in this country; practices that can, generally speaking, be universally applied.

Those who have viewed this subject from its technical standpoint are aware that, in so far as the present specified loadings on conductors and their supports are concerned, overhead distribution line construction in general can be improved but slightly by any of the modifications recently advocated. What is of far greater importance from this view-point (neglecting P.M.G. enforcements) is the minimum permissible overhead clearances of all suspended conductor- and wire-sizes for the different voltages for respective localities and locations, as well as the minimum capital outlay, etc., for respective crossing-span construction. One of the principal non-technical questions is that of wayleaves,[1] and it has long seemed necessary to obtain powers of compulsory expropriation for the purpose of installing certain overhead lines, as well as powers to make it possible to obtain wayleaves, quickly and on reasonable terms, from the owners and/or tenants, but preferably from the former *only*. In some countries electricity supply undertakings have the right of eminent domain, and some governments have long since realised that the advantages of the supply of electricity to rural areas must outweigh possible risk (if any) to the public by making provision for suitable construction standards, and by fixing wayleave rates, etc. per line-support and so forth. These and other pertinent questions which arise in the standardisation, economy, safety, construction, and extensions of overhead lines in general are matters requiring the closest study and attention in order to permit satisfactory development—rural and otherwise.

In the first place, we have to decide on the proper system to use, not for the present, or for to-morrow, but for all time. In making a comparison of the two currents (a.c. and d.c.) we are concerned chiefly with only a few questions, such as the relative initial cost and the relative reliability, neglecting for the moment the fact that d.c. is not suitable for distribution over very wide

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[1] See *Electrical Review*, 6th January 1928, p. 15, "Wayleave Rights," etc.

and scattered areas. To compare any system on the basis of normal smooth running conditions would be of little practical value to any one. At the outset it is of course desirable to have continuity of service for the a.c. system which is equal to or better than that of a d.c. system, assuming (say) a feeder is at fault, and allowing storage-battery auxiliary for the d.c.; furthermore, the a.c. system should at least be equal to or better than a d.c. system operating with storage batteries, assuming in this case a sub-station or distributing centre to be interrupted by a fault. For both systems it would have to clear itself or/and it would have to—

Burn off the fault, or provide protection; and

Ensure that failure of protection of a feeder or main would not cause complete shutdown; also

Limit extent of the section (or each section) or network to satisfactory operating size.

For the a.c. system the requirement would be to—

Burn off or burn clear the fault on secondary side of transformers, or provide protection;

Isolate the primary feeder and/or transformer fault (if any) at both supply and load ends; and perhaps

Provide duplicate or a multiple of feeder and/or transformer sources of supply to the secondary system of sufficient capacity and proper arrangement;

Restore sources of supply to secondary system quickly after an interruption is remedied, and, in the meantime, provide a temporary source of supply. Also relieve, as soon as possible, that source of supply temporarily overloaded during the emergency.

The a.c. system would of course give equal or better voltage regulation than the d.c. system, and, where regulators are not installed, the secondary mains would be made large enough.

The a.c. system would ensure ample transformer capacity and correct spacings on the distribution system.

The a.c. system would provide a sufficient number of feeders of proper size and would start out with a sufficiently high primary voltage.

The a.c. system would, when necessary, have induction regulators to stabilise the system voltage, and perhaps load the feeders evenly according to their respective capacities.

And the a.c. system would provide a secondary voltage as high as possible, consistent with satisfactory and safe operation of lights, motors, etc.

We thus see that the a.c. system is very flexible and is especially adaptable to extensive areas. And, of the different a.c. systems in common use, long years of experience have proved almost conclusively that the best distribution system is the *three-phase 4-wire system*, which system possesses the greatest flexibility, gives an increased kVA capacity, permits of a wider distribution, and therefore provides better service on remote extensions. It also offers the best combined light and power system over one circuit, and it permits of a cheaper construction, because it need only start out as a single-phase system, etc. (see also fig. 6).

In making comparisons of the a.c. and d.c. systems we must first know the magnitude of the service, and area, and transmission distance, because electricity supply, independent of the system (a.c. or d.c.), may call for:

Extra-high voltage and very large power carrying capacity;
or
High voltage and moderate power carrying capacity; or
Medium voltage and moderate power carrying capacity; or
Low voltage and small power carrying capacity.

In this country these pressures are classified as follows:

Extra-high pressure is any voltage above 6600 volts;
High pressure is voltage not exceeding 6600 volts;
Medium pressure is voltage not exceeding 650 volts;
Low pressure is voltage not exceeding 250 volts.

As a distinction from this classification of voltages, in U.S.A. and Canada we have:

Extra-high pressure is any voltage above 150,000 volts;
High pressure is a voltage not exceeding 150,000 volts;
Low pressure is a voltage not exceeding 600 volts.

The extra-high voltage and large capacity lines consist of the primary supply to main sub-stations or/and direct supply to transforming centres, with or without intermediate taps. These are provided for transmitting large blocks of power from a more economical and/or more efficient point, such as the selected points of, say, a "grid" system such as that this country is to adopt. For such bulk supplies to main sub-stations and/or transforming centres, the wooden pole or frame construction is in every way satisfactory; a duplicate or loop for such like main supplies is always advisable whether wood or steel is used for the line-support. The standard voltage may be 33,000, or it may be four or more times this figure; for bulk distribution, 33,000 volts would seem to be a desirable pressure.

The lines of high-voltage and medium capacity may form the primary supply to main sub-stations and/or transforming centres, or they may supply direct to the distribution transformers at various parts of the network, in which case other supply lines may (or may not) be installed for the purpose of reserve or for emergency service. These are the primary feeds for all areas, and the voltage may be anything from 3300 to 33,000 volts, depending on the territory, class of construction, distance, load, and/or its character, etc. These voltages would be suitable for the particular conditions and for safe transformation to low-voltage distribution mains, if desired.

The medium-voltage as well as the high-voltage systems may supply somewhat similar secondary distribution; this may consist of mains joining all the distributing transformers into a general network, or may consist of mains which form an independent section (or sections) completely isolated from other parts of the general network, but which have (or can have) the mains from adjacent transformers in the section or sections (as the case may be) tied into one network, or may consist of mains fed direct from a distributing centre and kept isolated from secondary mains fed from other transformers—this latter method being quite common in rural districts.

The lines of low voltage and small capacity are, like the d.c. system, generally for local areas giving light and power service direct at a suitable voltage, *i.e.* 400/230 volts for this country, and classed as *medium* voltage.

As the secondary network is usually a costly undertaking, it is important that:

It should permit of minimum maintenance; and
Be low in first cost; and
Be rugged in construction; and
It provide a reliable supply; and
Be of simple construction and require the least number of switching and protective devices.

The primary supply should provide uniformity of transformer sizes, also provide for their proper location and loading. At the commencement it may be best to adopt that system (the three-phase) permitting a *single* primary feeder for bulk as well as other loads, and, where possible and desirable, adopt a voltage to avoid step-down transformers. Also it should provide easy connection and disconnection of feeder to network, and a *single* secondary main (three-phase 4-wire) so that both light and power can be given over the same circuit without a flicker on the lighting services when motors are started. And, generally, it should provide for satisfactory methods of metering.

Sometimes a line is run directly from a main sub-station or from a transforming centre to a distributing point, and, when the load-density has reached a certain value, another line (or lines, or circuit, or conductor) have to be run in the same direction—these form *radial* lines or circuits from the one source of supply. Depending on the direction of lines or/and the form of the area and number of distribution points, the system of distribution can be looped in, forming *ring* lines. This method is often more economical, and is desirable in case of failure of any one in-coming source of supply. When the load has grown to an extent requiring more conductor-carrying capacity, a radial line can be run direct from the main sub-station to the transforming centre, or, from the generating station to the main sub-station, as the case may be.

Resulting from tests and investigations carried out by the author during 1925–26 for the purpose of ascertaining the relative useful insulating values of wood and steel supports for conductors, and also the most effective position and relative insulating and protective value of a continuous earthed wire, in contact with as well as insulated from the wooden support, the author has come to the conclusion that all possible insulating value of the wood [1] throughout should be maintained at all times.

Looking over designs and construction practice of this country, one sees everywhere the continuous earthed guard wire (see p. 199 and figs. 7, 17, 18, 40). The law demands its use, and therefore, as it must be used, why not *use it properly?* Its present use can in some way be likened to installing an alternator for the purpose of running smoothly, neglecting the fact that by adding a little thing called an exciter (requiring not more than 2 per cent. of its total kVA capacity) it can be turned into very great value and *properly used.* Just so with the continuous earthed guard wire; in fact it can be turned to a decidedly useful and profitable value. For instance, where single-phase 2-wire or three-phase 3-wire primary distribution lines are considered, it can be made much more effective than present practice, and it can be turned to proper use. Taking the three-phase 3-wire primary distribution circuit, by right design and construction the installation of a continuous

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[1] See p. 450 of author's book, *Overhead Electric Power Transmission Engineering*, C. Griffin & Co., Ltd.

earthed guard wire can give us the following remarkable advantages over present-day practice:

(1) For equal or much less voltage strain, and using present-day construction standards, the kVA output for equal percentage volts drop can be increased by an amount ranging between 250 per cent. to 300 per cent.

(2) For approximate equal voltage strain on the line insulators, and by modifying present-day construction standards, the kVA output for equal percentage volts drop on the line can, with approximately equal factor of safety of line insulation, be increased several times.

(3) The arrangement of conductors and the continuous earthed guard wire for (1) remain the same, but the latter would be properly insulated from the wood pole and would be of the same metal and size (or 50 per cent. of the size) of each of the line conductors, and the circuit would be three-phase 4-wire. The continuous earthed guard wire would be as effectively earthed as at present. By this method the transformers need not cost any more per kVA, and the line insulators need not be changed as the insulation strain is not so great. This is obtained on the basis of present construction standards, properly modified. With modification of construction we obtain better line protection and a better operating line than with present construction practice.

The above refers to present-day design and construction standards of this country such as shown in figs. 7 and 17. The common *position* of the continuous earthed "guard" wire strung from pole to pole need not be changed; it is less efficient but safer than one located at the top of the pole, provided it is as effectively earthed and is equally well installed, because it cannot fall on conductors, and it *may* touch or catch a broken conductor as it falls, etc. Earthing the crossarms and pins to it is bad practice, especially in a wet country like this, and it is dangerous practice in a country in which lightning is frequent; conditions may not be fixed by earthing at four "equi-distant" points to the mile (which differs, generally, from four equi-resistance points), in place of earthing at each support. A continuous earthed wire, run from pole to pole, is likely to be a more active combined lightning conductor and arrester than any other single piece of protective apparatus on the system, and, as the wood pole is used as the path for lightning discharge, there is a relatively greater chance of it being split or shattered at the intermediate points, etc. Instead of using the system and method referred to herein, the *present* practice in this country is to provide surplus insulation, *i.e.* larger insulators for each conductor at each support, to install porcelain strips, etc. on the top of crossarms (which alone costs as much as would an insulator for the earthed wire), and to take away all insulation of wooden supports, etc. (see p. 141). All this supports amply the view that by proper design and construction (see p. 140) we can convert the *existing* 3-wire wood pole line into the proposed new three-phase 4-wire line (in no way excluding advantages for single-phase lines) by insulating the continuous earthed wire and using it as part of the electric circuit, etc. Thus we are able to deliver relatively more energy over the same line for equal percentage voltage drop and equal percentage power loss, and at the same time have a far safer line and get far better operating conditions. Surely we desire to apply the best distribution practice as well as the best system for the distribution of electricity, and (unlike the d.c. system) one that has no end or limit to its magnitude and/or area to be served? We obtain this *by the proposed system*, which also gives us relatively more power, a safer and a better operating line, without any further expenditure, *i.e.* for the same amount of money. This being so, it is inconceivable that the requirements of the P.M.G. should be allowed to hamper or stifle progress and development in this country (see also p. 136).

Long experience and experiments have shown us that conditions on wooden pole lines *without* earthed wires in direct contact with the poles, and with as little metal as possible up the poles, are safer from lightning than when equipped with earthed wires, or wire, metal arms, etc. Under such conditions, and with a faulty insulator, a breakdown would be resisted by the insulation of the wooden supports to ground. For this and many other countries there would be little or no fear of a direct hit by lightning, and where this is at all likely, a spark-gap can be effectively used just as required for the neutral conductor (see p. 216). Should an earthed wire be used, then the insulation to earth is much reduced—*i.e.* the flash-over value of the insulator itself, a large part of the crossarm, the larger part of the pole, as also the soil surrounding and in contact with the pole, which is often sodden in creosote and of some insulating value. Therefore, a breakdown of a bonded insulator with this practice is almost sure to cause burning of the crossarm and/or the pole; hence, any practice permitting this is bad. It is easy to distinguish between a burning or charring by a power arc and that caused by lightning; the former will always charr or burn a wooden support, while the latter will split or shatter the support. It is dangerous practice to provide means for aiding or causing this latter condition as is so commonly done at present (see pp. 196–201).

The question before us is: what constitutes the best, safest, and more economical electric circuit and pole line? As regards the system, we can definitely decide on using three-phase 4-wire for primary and secondary distribution, and single-phase for certain branch lines. The choice of primary distribution voltage will depend on the magnitude and class of load and area to be served; a good medium value is 6600 volts. The principal requirements are many and varied, and will be dealt with later. First let us consider the existing obligations to see if we are allowed to cope with this question satisfactorily. We are sometimes told that this is the only country where engineers claim to provide and lay underground cables as cheaply as overhead lines; taking this for granted, what greater proof do we require to show that something is radically wrong with the regulations (see p. 136)? Standard of risk or standard of safety depends on the *real* permitted risks and *true* reasonable safety. In this country *standards* must have taken the wrong turning at the start, that is to say, concentration was, apparently, on the provision of devices to catch or touch a conductor as it fell, to the neglect of close study of its resulting reaction on costs, safety, operation, etc. on the line itself, it being accepted that the more correct standard of safety and construction was to prevent a conductor from falling, and to provide means to retain and maintain maximum aggregate insulation as well as maximum mechanical strength of all the materials *actually needed* for the best, safest, and most economical electric circuit and pole line.

Obviously we should adopt, for this country in particular, that system presenting the least number of features likely to be objected to by the public, *i.e.* one using the least number of feeders, crossarms, etc.; and we should so locate lines that they are in the least objectionable positions, such as alleys, back streets, or gardens, and other places not used as main thoroughfares, or other public spaces. For *combined* light, heat, and power supply we should use that system (not systems) requiring the lowest number of conductors, least conductor clearances to earth, the smallest total sectional area of conductor, one offering the greatest possible diversity, requiring the lowest number of transformers and the lowest total kVA capacity of transformers for the combined load, as well as the lowest number of service connections for the combined load, etc.; and, a system that possesses the greatest flexibility, offers the greater *system* kVA capacity considered as a whole, and also provides the best service on remote extensions such as is generally required for outlying areas and rural service. Also we should provide that system (the proposed system) capable of starting out for a given service with the lowest possible number of conductors (one only), using the continuous earthed wire as the neutral or return conductor modified as proposed herein, *i.e.* used for combined earthed wire or earthed guard wire, as a protection device for tripping the circuit in the event of a fault, as a neutral return conductor, and as a means for earthing the pole through a spark gap, etc. The system to accomplish all this is the proposed new *three-phase 4-wire* given here for the first time (see fig. 6).

For distribution of electricity a single pole is the general rule, and the best pole is one of smooth round outline possessing ample mechanical strength and high, or good, insulating properties in the material used. It should be as short as practicable, consistent with minimum permissible overhead clearances as well as future requirements. At present the wood pole comes nearer the ideal and is the only pole in use that has the most ideal outline to resist stresses. It has equal strength in all horizontal directions, and the greatest elasticity to equalise unbalanced loadings, and has very useful insulating value; it is also economical in first cost, is efficient in working, and, electrically, it offers the safest line.

For equal resisting (or bending) strength the single wood pole has a diameter slightly less than 1·7 times the "A" or "H" frame, commonly called two-pole structure. Where the base is rigidly held, the strength may be taken as nearly double that for ordinary setting in soil, hence there is greater need for caution in the case of the "A" and such-like frames than for single poles.

The bonding of pole ironwork provides a more dangerous line, hence it should be avoided. It is unwise to bond the insulator-pins and connect them to a continuous wire strung from pole to pole; a faulty insulator endangers the whole line. And, it is equally unwise to bring the earth up to and in contact with a wood pole, because the safety of the line is much impaired, bird and other troubles are increased, the line operation is less reliable, and the line is made more dangerous. In lightning areas the continuous earthed wire can be used for earthing the pole (if required) in the same way as earthing the neutral conductor for lightning protection, *i.e.* through a spark-gap from the pole to the earthed wire (see fig. 6).

Wooden crossarms (*oak* in particular) are entirely satisfactory and equally as durable as, and no less reliable than, the wooden pole. As they cost but a very small fraction compared with a wooden pole, and as they consist of better material and are better treated than, and not pierced or so roughly handled as a pole, there is little or no practical reason why they should not be used very generally as in other countries, especially as this country has relatively greater wet seasons, etc. The wooden crossarm permits of the safest and best operated line which, apart from cost, is among the chief requirements. For distribution work in general they should take preference over all other materials (see fig. 19). On straight-line construction only one crossarm is required for primary feeders; if it is a single-phase lighting branch it can be placed on one side of the arm, and the secondary on the other side of the pole on the same arm. This offers the safest line taken from two of the most important view-points, namely, wind-pressure and high-pressure crosses, and a much shorter pole can be used. Double crossarms are required only at corners, crossings, and where very heavy conductors and/or long spans are used. For distribution work in general, single crossarms and single insulator-pins are required (see also fig. 19A).

(Stays are necessary where conductor stresses are not balanced; they are useful in preventing increases in sag in adjacent spans. In all cases they should be insulated from the poles (see p. 47).)

The most economical line operation is secured when the insulator, pin, and arm work together, and only when considered in this respect can maximum effective insulation and life be expected. Bonding insulator-pins increase the stresses imposed on the insulators, and earthing the pins imposes additional strain on the insulators. A better and safer line is secured and improved operation is obtained and maintained from unearthed and/or unbonded insulator pins. Insulators of much higher rating are required for equal satisfactory service when the pins are earthed; this also applies where the earth is taken up, and in contact with the pole *for any other purpose.*

The efficiency of a tie-wire depends on the wire used; the tie, whether bare or insulated; the size of conductor; and how the conductor is placed on the insulator. For straight runs, the conductor is placed either in the top groove or on the side of the insulator nearest to the pole. At corners or angles, the conductor is placed in the side groove so that the insulator and not the tie-wire takes the strain.

For all distribution lines, designs are based on strength of supports in the transverse direction of the line except at corners and terminals; that is, on the wind pressure transverse to the line. Therefore, for equal overall diameter of conductors, the copper conductor has a large margin in its favour over all other conductors (also see p. 129). For equal voltage strain to earth, copper also offers the smallest size of conductor for equal delivered load and loss; hence, mechanical supports for equal span are less in cost, etc. (also see p. 71). In general the stranded conductor is safer than the solid conductor. In certain urban areas and for certain voltages, conductors may be required consisting of rubber-filled tape with a serving of jute saturated with tar and a tape over this covered with weatherproof cotton braid. Proper splices, joints, and method of soldering must be observed. It may be found better in the long run to deal with excessive voltage drop by additional copper than by voltage regulators.

Primary feeders are protected at the source by oil switches. Duplicate or immergency feed, and sufficient sectionalising or isolating link or disconnecting switch-points, and/or automatic reclosing equipment, should be installed. Distribution transformers are protected by fuses, switches, or reverse-energy circuit breakers. The low-voltage network is usually protected by fuses; where possible, parallel or interlace feeders, so that at least every alternate transformer is fed from a different feeder or phase. The usual faults are earths, short-circuits, and transformer failures. Circuits should be equipped with the usual protective tripping features. Service taps should not be too long and should be taken off as straight and as level as possible, allowing liberal sag and using approved insulating spacers where tapped other than at the pole.

The neutral conductor is at least as important as any of the phase conductors. The worst thing that can happen is to have it break. The best results are obtained by earthing the primary neutral at the station or the transforming centre, and at other convenient parts of the distribution system, and earthing the secondary neutral at or near the distribution transformer and on the consumer's premises. Multiple earths generally provide a better and safer construction and system. The location of the continuous earthed guard wire is reasonably effective (see fig. 7), but it is not put to proper use; by the system and method proposed herein it can be put to several valuable uses, one being that of neutral return conductor at zero potential. If the neutral conductor is of the same size and material as the phase conductors (whether used in emergency cases as a phase conductor or not (see p. 198)), for equal safety it should be strung to greater sag, because it is subjected to greater mechanical load and it derives no benefit from increase in temperature such as the current in a phase conductor, and will collect more ice and will retain it longer than any phase conductor. If it is smaller in size, a somewhat greater sag is required for the same span-length and same conductor material.

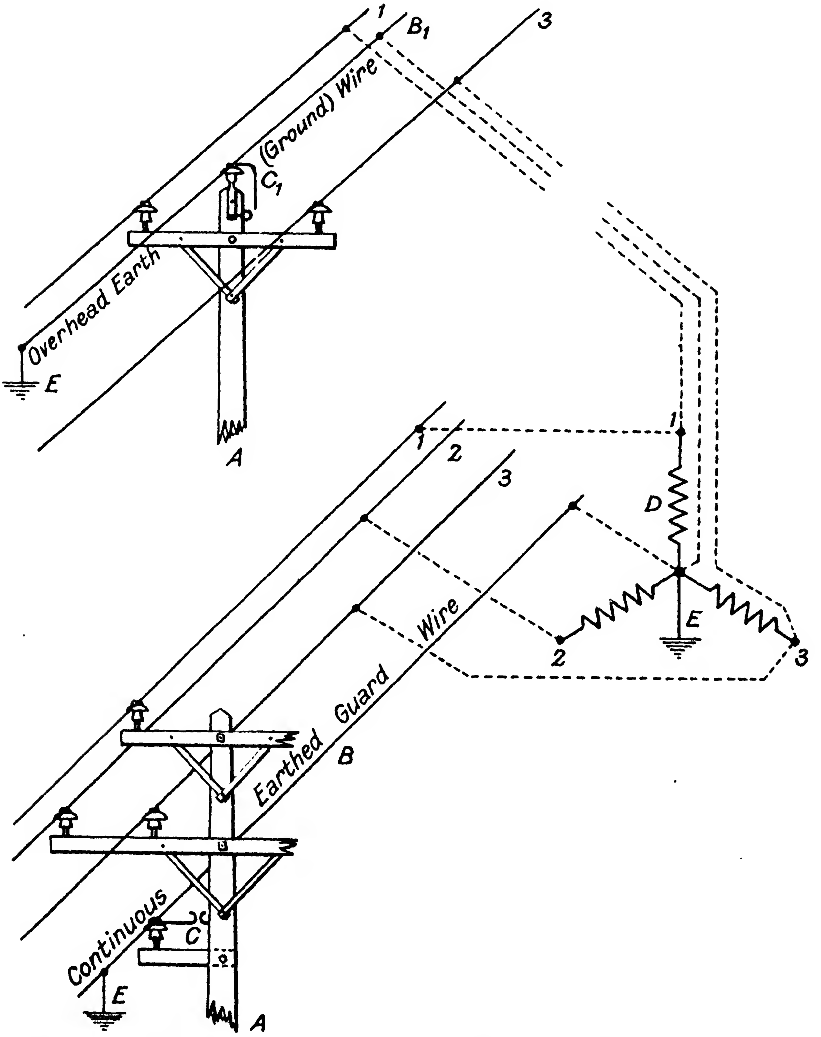

FIG. 6.—Proposed distribution system; see also fig. 32B. (This system permits maximum reliability, maximum economy, maximum service, maximum safety, and maximum earning capacity. For equal percentage voltage drop, equal maximum voltage with regard to earth, equal insulator rating, practically equal total sectional area of conductor, equal strength of supports, and equal span-length, etc., this system permits of greater kW to be carried, best protection, and best operating conditions, etc. Read pp. 15–25; also 196–201 for a better understanding.)

In distribution work ordinary spans are the general rule; a 240-ft. span is excellent, as it is about the longest, most economical length where wood poles are used, and it permits of very general and safe use of wood crossarms. As this length of span is not determined by the mechanical strength of the conductor, the risks (if any) are in other directions. ✓

Although inductive unbalancing is important, more in distribution than transmission work because of greater currents and closer regulation, etc., the arrangement of conductors in distribution work rests largely with such matters as clearance requirements, swinging, sagging, working spaces, number and sizes of conductors, etc. The horizontal arrangement usually offers better all-round advantages than the vertical arrangement; for general conditions, we can afford more horizontal than vertical space to provide equally safe clearances of conductors. Where more than four conductors and two circuits of different voltages are used, both spaces are usually taken up. The best arrangement of conductors for safe working clearances, keeping in mind future requirements, decides the separation of the conductors and the economical size of pole. Taken as a general rule, the largest conductors should be the lowermost on the pole and closest to the pole, and for the highest-voltage conductors the exact opposite practice should be followed. At crossing spans conditions are different to straight-line construction, and decisions can be taken from p. 52, which give the best and most suitable practice to adopt. Telegraph and telephone wires should never cross (nor be strung) above or over h.p. conductors. For equal size, the location of the neutral conductor over (above) a phase conductor is dangerous, and imposes a greater loading on the pole if it is not given a greater sag; this position is common in rack construction, the idea being that should a h.p. (h.t.) conductor break, it would do less damage falling on the neutral conductor. However, it is generally overlooked that as this conductor does not normally carry current it will be subjected to greater mechanical loading and to unequal sag in relation with the other conductors. Taken as a general rule, the highest-voltage conductors should always be uppermost. It is both bad and dangerous practice to have workmen climb through or pass h.p. conductors to work on l.p. conductors located above or on a higher plane. In deciding the spacing for horizontal arrangement, it is necessary to know the maximum angle of swing of the conductors (see p. 72); maximum angle of swing ($\tan \phi$) is equal to the wind pressure on conductor divided by the weight of the conductor per unit length respectively (see Table VII).

There still exists a certain controversy as to what is the best distribution system and line construction. As with most things, taken as a general rule, the best is the cheapest in the long run. Unfortunately there has been too much talk about "the most economical" being the best and most satisfactory; this so-called "most economical" invariably lacks many real and vital *most economical* factors, which, when included, mean more truly *the best* is the cheapest. Very often, and only around the initial stage, is the so-called "most economical" or initially cheapest the best, and it often quickly becomes expensive and more dangerous.

To improve operating conditions and minimise the probability of service interruptions, before deciding on the arrangement of conductors, etc., it is necessary to bear in mind that:

Their height above ground-line, their number, the length of line, its location as to relative exposure, as well as the length of underground cables connected to the line, are all very important factors.

The higher the feeders or mains the greater the hazard to transformers and line, etc.

The greater the length and greater the number of conductors and wires, the greater will be the exposure to lightning, winds, etc.

Joint occupancy of power and communication circuits permits of a better shielding value from lightning, etc., for the power conductors in particular (see also p. 66).

The greater the line insulation the greater will be the protection against direct stroke of lightning and high-voltage impulses of steep wave front; therefore, distribution mains, also inferior wires and defectively insulated at the supports, are the most liable to dangerous external pressure rises, against which protection by suitable discharge to earth is required. Pressure rises due to induced voltages are the most dangerous in distribution lines; however, when effectively cared-for, protectors such as arresters, chokes, absorbers, suppressors, earthing coils, and resistances, etc. are often not required. For the best construction (against line being struck by lightning) the main or phase conductors should be shielded and the lightning charge dissipated over the earthed neutral conductor or/and over the continuous earthed (ground) wire; the *combined* earthed neutral conductor and continuous earthed (ground) overhead wire (see fig. 6) not only eliminates the use of one conductor from the present-day line practice in this country, but the best all-round protection against dangerous pressure rises is secured. To eliminate trouble from a stroke of lightning, an efficient overhead earthed wire is the most reliable and is a satisfactory means and protector; to eliminate trouble due to high-voltage impulses and steep wave front, shattering poles, etc., spark or horn gaps, and other forms of protectors can be effectively used (see fig. 6); and, to eliminate trouble due to high-voltage static and arcing earths, etc., an effectively earthed neutral conductor is about the most suitable protector.

Proper location of the earthed neutral conductor permits of considerable shielding from lightning, etc. (see also fig. 6).

Locating lines parallel with and adjacent to trees results in a safer line from lightning effects, winds, etc.

Where a continuous earthed wire is used, it is well to avoid iron or steel, *i.e.* use non-magnetic conducting material, copper or copper-alloy for preference, as low resistance path through the wire and the earth connection is of considerable importance; this also applies to fig. 6.

The value of earth resistance to be considered as dangerous depends on the amount of current which the earth connection will carry, as well as the maximum strength of the insulation which is to be protected, both of which are improved and established by proper construction, as outlined herein.

Long experience has shown that the merits and life of wood pole and frame construction, properly chosen and impregnated and properly installed, are decidedly favourable. And, for a line of proper construction (see fig. 6) there is less lightning trouble, less bird and other line troubles, and a superior operating line for equal insulator rating than one of steel construction in particular.

Each steel support is a lightning conductor and often a lightning "arrester" (using the word "arrester" in its true sense), and it is most efficient as such when most effectively earthed and when carrying the greatest amount of metal and covering the most space. Hence the risk of interrupted service due to faulty insulators, etc. is considerably increased, even though there is a smaller number of insulators and supports, by introducing the longer spans, because breakdown is generally not due to a larger number of weak spots but rather to one (or more) "hot," or highly stressed, or excessively weakened, insulation spot—in all things it is always the weakest, or the weakest of the weak, that fails.

As regards distribution transformer failures, these are due to such factors as the type of installation; the system used; the transformer size, type, and age; whether new or rewound; their location; type and grade of line construction; the connected load; previous transformer and/or fuse failures; whether earthed or otherwise, etc. Also, failures are due to limitations in protection (independent of lightning arrester protection), such as currents from several circuits through earth connections of moderate resistance, entrance through the secondary side, and high earth resistance, etc.

In trying to burn off a fault (on a non-regulated line in particular) an overhead circuit cannot be compared with an underground cable system, and the a.c. system cannot be compared with the d.c. system; for the former (in both cases) it is not so easy as is the general impression to burn off a fault, even in the case of a line voltage as high as 15,000.

Summarising but a few of the principal merits of *the* system and line, it is quite apparent that:

> We desire a system of distribution, as judged from every point of view (which includes summation of every advantage), that is the best system. This centres around the three-phase 4-wire system (specially study pp. 196–201).
>
> We want a system capable of starting out with the least number of line wires and conductors, and least total conductor sectional area; this likewise favours the three-phase 4-wire system.
>
> We want the simplest system, and one that offers the best voltage regulation for equal delivered load, distance, etc.; this also favours the three-phase 4-wire system.
>
> We want a system that, so far as protection to apparatus, etc. is concerned, the normal voltage to earth can *under no conditions* rise to more than 58 per cent. of the normal voltage between line phase-conductors; this also favours the three-phase 4-wire system.
>
> We also want *a system* that prevents the potential of a neutral point from a serious change from earth potential as well as which offers free discharge of electricity, and with it we want *a line* possessing the ability to keep down to a minimum (and one that will rapidly dissipate) the quantity of lightning potential superposed upon it; this again favours the three-phase 4-wire *system and line*, such as shown in fig. 6 (see also p. 198).
>
> Dangerous system disturbances arise from external and internal causes; as a general rule most of the former are caused by lightning, and the latter are due to switching, arcing earths, and short circuits. For the former it is obvious that, as *the* danger is from a phase conductor to earth, the safest line and system is that which provides for the greatest reduction in the intensity of over-voltages due to lightning, etc., as well as the greatest damping effect on any high-voltage wave or disturbance travelling along the line; the system and line construction shown in fig. 6 are most suitable

for meeting these external dangers, for giving the best and most effective relay protection for the system and line, for eliminating troubles of any kind arising from static pressure rises and arcing earths, also for giving the greatest protection from high-voltage strain. For the latter there are many

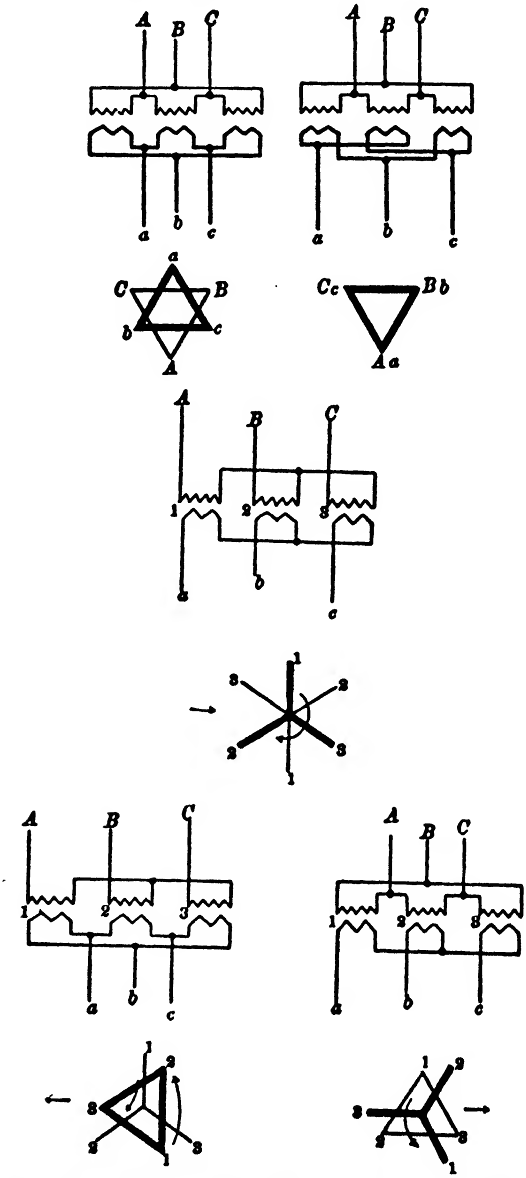

FIG. 6a.—Showing three-phase system transformation.

relay and impedance protective devices on the market to choose from; troubles from arcing earths are eliminated by using the system shown in fig. 6 (study pp. 196–201).

During the last few years line construction has taken a turn from steel to wood, and while the price of the wood pole keeps its present level, this type of line construction will continue to be erected in preference to steel or reinforced concrete. Of special interest is wooden construction throughout for the higher-voltage lines; this practice is one of the best possible recommendations to the general adoption of wooden construction for distribution lines. The following table is a representation of line construction during the past two years. It is for transmission work, but is of interest in showing the trend of the latest practice, *i.e.* wooden pole or frame construction, use of single-circuit lines, very general use of copper conductors, etc. All the lines given in the following table are important, and have been decided upon only after a very careful study of general conditions by engineers with wide experience in line construction and operation.

TREND OF PRACTICE OF RECENT LINE CONSTRUCTION SUCH AS WOOD POLES OR FRAMES, GENERAL USE OF COPPER CONDUCTORS, ETC.

Company.	Line Voltage.	Miles of Circuit.	Conductor (*Copper*).	Span (Ft.).	Supports.
City of Seattle Lighting . .	165,000	120	0·630-inch	600	Wood.
Utah Power and Lighting Co. .	132,000	82	0·575 ,,	612	,,
California-Oregon Power Co. .	132,000	74	0·575 ,,	600	,,
Idaho Power Co. . . .	132,000	81	0·575 ,,	600	,,
Puget Sound Power and Lighting Co.	110,000	61·3	0·528 ,,	. .	,,
Southern California Edison Co. .	66,000	260	0·528 ,,	200	,,
Eastern Oregon Light and Power Co.	66,000	57	0·373 ,,	475	,,
Southern California Edison Co. .	66,000	41	0·418 ,,	200	,,
Nevada Valleys Power Co. .	66,000	36	0·292 ,,	300	,,
United States Bureau of R. .	66,000	19·3	0·332 ,,	440	,,
Idaho Power Co. . . .	66,000	16	0·332 ,,	350	,,
Washington Water Power Co. .	60,000	22	0·147 ,,	365	,,
Pacific G. and Electric Co. .	60,000	15·2	0·232 ,,	300	,,
Portland Electric Power Co. .	57,000	3·5	0·418 ,,	200	,,
Puget Sound Power and Lighting Co.	55,000	25	0·528 ,,	. .	,,
Great Falls Power Co. . .	50,000	70	0·147 ,,	300	,,
Albuquerque G. and Electric Co.	44,000	17	0·332 ,,	275	,,
Trinidad Electric T. R. and G. Co.	44,000	15	0·332 ,,	230	,,
Salt River Valley W. U. Assoc. .	44,000	13	0·418 ,,	. .	,,
Arizona Power Co. . . .	40,000	21·2	0·332 ,,	393	,,
United States Bureau of R. .	33,000	58	0·332 ,,	250	,,
Portland Electric Power Co. . .	33,000	30	0·370 ,,	150	,,
Southern Sierras Power Co. .	33,000	20·3	0·184 ,,	300	,,

Note.—The differences in span-length for relative size (diameter) of conductor is due to the class of territory crossed, the loading district, etc.

For distribution lines, wooden construction is universally in general use, and will continue to be as (or more) generally used in future years because of the better understanding of its merits. At the present time it is the kind of support more generally used than any other, but unfortunately it has been and is being used in an inefficient manner—that is to say, full advantage is not taken of wooden construction throughout (absence of steel) and its useful insulating properties, which can be increased and maintained to best advantage by proper impregnation; nor is full advantage taken with regard to line construction and protection, etc. along the path of highest efficiency and reliability. The author, therefore, can make no apology for offering this work at an opportune stage in this country's electrical development. In view of the fact that the *three-phase* system is to be *the* standard system for the entire country, there is further reason for concentrating special attention on the three-phase 4-wire and single-phase 3-wire distribution systems. Furthermore, at this initial stage in the electrical development of this country in particular, and also because of its existing line construction practices, there would appear to exist very good reasons for proposing a system of electrical distribution possessing outstanding merits or, at least, deserving of special study based on the world's best and safest practices (pages 15–25, also 196–201 are deserving of special study); but quite independent of these matters, the text throughout boils down the world's *best* most essential factors and practices. In certain parts of the world, also for cases where interconnections are contemplated, and where the two best and most economical polyphase systems (the three-phase 4-wire and the two-phase 5-wire) are used, the method of line construction and system-transformation proposed in fig. 32B should provide for the necessary adaptability and usefulness of the two most important symmetrical polyphase systems.

The practice of joint occupancy of pole lines (see fig. 8), as yet non-existent in this country, due chiefly to the almost impregnable objections and circumstances of those responsible for operating the communication circuits, is just touched upon in the text. Only an equally strong combating Government department can best bring about this necessary change, which has in other countries already given economical and satisfactory service to both of these distinct public utilities for more than twenty-five years.

CHAPTER II.

ASPECTS OF LOCATION AND DESIGN OF DISTRIBUTION LINES.

Distribution lines differ from transmission lines; the latter transmit energy from one point to another with usually no tap between, while distribution lines are designed to conduct energy from one point to a number of other points, involving many taps and branches. Such lines are very rarely designed for the demands of the immediate prospective consumers solely—the design and construction generally allows for a growth over several years.

For the primary system of distribution there is the choice of using radial or loop feeders. The form of radial lines are where one route is the practice, *i.e.* where the points of distribution are in the same direction from the source of supply. Loop feeders pass out of a station and describe a loop. The simple arrangement of primary mains is to run out feeders, or a feeder, to terminate at or near the electrical centre of distribution of the particular area to be served, and from this point take off branches in the directions desired; in this way each obtains the same advantage of voltage regulation, *i.e.* voltage regulation at the centre of distribution at all loads. Whether single or polyphase, the centre of distribution can be located with reference to the electrical centre of the load in its particular area and each regulated for voltage separately, which permits feeders to be loaded more heavily than is possible when the load is distributed from a single centre or point.

It is poor practice to load up a wooden pole or frame with metal work; it is still worse to bond all the metal work, because any defective insulator makes the whole of the pole or frame ironwork alive and a danger, as viewed from many standpoints. If much development in rural electric supply is expected in this country, many existing obligations imposed on undertakers must first be relaxed.

The size of insulator depends on other things than line voltage, such as locality and the atmospheric and other conditions, and the kind of line construction used. The proper location and disposition of conductors depends on the line voltage, their size, and the type of line construction used. In distribution work the arrangement of conductors is very important, as climbing and working clearances must be amply provided for. For primary distribution using the three-phase 4-wire system, the four conductors are best placed on the top crossarm, two on each side of the pole; the neutral conductor may be placed on the tree side or on the road side whichever is locally found best. The secondary l.p. and m.p. distribution may be rack or crossarm construction, depending on the number and size of conductors, the length of spans, and other conditions. Crossarm construction, for the same insulators used, permits of a safer and better insulated line than one of rack construction.

In the location, design, and construction of an overhead line, at least the same amount of care and technical knowledge is needed as for an equivalent underground cable installation. For line location, some of the principal factors requiring consideration at, or before, the time of design are:

Satisfactory route as regards safety, accessibility, and costs;
Reasonably straight route;
Satisfactory span-lengths for safe clearances;
Safe and satisfactory lengths, and number of line-supports of the proper type and strength;
Maximum strength of materials for least cost;
Satisfactory location for the line-supports themselves;
Minimum cost of foundations and settings;
Minimum cost of materials, freight, haulage, handling, distributing, and general labour;
Attainment of the highest factors of reliability, and safety from all sources;
Property value and nature of ground, particularly at corners or terminals, which usually are points of special importance, as foundations, and such locations, usually form one of the weakest parts of a line.

And, in the location of rural and other lines it is of importance, from several view-points, to provide for:

Ample clearances from fences or boundary lines;
Avoid areas or districts subjected to prevailing gusts of wind;
Avoid districts subjected to atmosphere polluted by chemical fumes, soot, fog, salt spray, smoke, dust, etc.;
To keep away from busy highways, chemical works, telegraph and/or telephone lines, very low and/or swampy ground, etc.;
Pay due consideration to the value of property crossed;
Reliability of service;
Accessibility for inspection;
Keep in mind, in deciding on the economical span, to have sufficient overhead clearance of conductors and wires at all points;
Due considerations to matters likely to affect construction of any part of the entire line.

Proper location can be expressed fairly well in the following ew words: Higher mechanical and electrical factors of safety, heaper maintenance and better operation.

Wayleaves in villages or towns can no doubt be obtained on very short notice from the Electricity Commissioners by permit—or franchise in other countries—for the use of streets, alleys, or other public thoroughfares, or over private property; wayleaves can more often be obtained by easement. In obtaining private wayleave care should be taken to avoid all clauses in contracts which would be, in any way, detrimental to the construction or operating of the line. In obtaining wayleave the following points are important:

See that it is the most desirable route;
Note general character of territory crossed;
Study more than one route and select the best;
Study the location and magnitude of all angles—their costs and hazards;
Study location of section lines and corners;
Study all property boundary lines;
Note carefully the length of line through each piece of land and the character of land crossed or to be crossed;
Make a close study of railway and highway crossings as well as telegraph and telephone line crossings, or to be crossed;
Study possibility of parallel lines with telegraph and telephone lines for some distance, also joint occupancy;
Make a close study of the topography;
Study the profile and prepare map of proposed line;
Study best location of line-supports by staking, etc., etc.

To fulfil these requirements satisfactorily it is necessary to have a map covering the complete route, or line extensions, showing both plan and profile for construction purposes and for records, etc. (see p. 251). On the profile shown, the poles should be located so as to take advantage of changing slopes and so forth, and to occupy suitable locations for crossings over roads, highways, etc., care being taken at all locations that the line insulators and supports will carry a sufficient proportion of the weight of the conductors to prevent dangerous side-sway under wind-load conditions. There should be at least one of the maps showing land purchased, if any, in fee or obtained by easements, giving bearings, property boundaries, distance, etc.

It should not be overlooked that the most advantageous line-support locations, and the most favourable clearances of conductors, are of little avail if the insulator tie-wires or clamps securing the conductor or wire are not effective and reliable; with an increase in tension of the conductor the diameter of the stranded conductor is decreased slightly, and slipping of ties is likely to occur.

The route and location of lines (for all voltages) should be selected so that the total cost of the completed line will be a minimum in so far as this is consistent with considerations of accessibility for maintenance, winds, and other storms, and the effect of local climatic and atmospheric conditions *on insulators* as well as other parts of the line.

Where a line is to be located on a public street, its effect upon adjacent property should be given due consideration; and permission should be obtained, where there are growing trees, to cut or lop all trees likely to be an obstruction to the construction and safe operation of the line.

When crossing private or government land, the wayleave ought to be well cleared of brush, and the trees on either side of the line, which might injure the line by falling, preferably should be cut down and removed if permission to do so can be obtained; all brush and débris should be piled and burned, and the wayleave cleared for construction and for facilitating its inspection during operation. Great care should be exercised to prevent any destruction along the wayleave without the previous permission of the owner (or/and tenant) of the property. Over private wayleave the centre line of poles usually conform as closely as conditions will permit to the centre of the wayleave obtained.

Distribution lines differ from transmission lines, which latter transmit energy from sending to receiving stations with no taps between, while distribution lines are designed to conduct energy from one point to a number of other points involving many taps and branches; in other words:

Distribution lines are divided into many circuits;
They are designed to carry much less energy;
The voltages employed are much lower;
Their designs are not so rigid, generally speaking;
Their insulation is less difficult;
Short circuits are usually less destructive;
More general use is made of wooden construction throughout, *i.e.* wood poles and wood crossarms and wood pins, sometimes wood braces.

Distribution lines should rarely, if ever, be designed for just the demands of the immediate prospective consumers, in fact this is bad practice; also, in making extensions, proper provision should always be made for a growth over several years.

When consumers are from six to ten miles from the source of supply, 6600 volts is a good standard, and when they are from ten to twenty miles distant, 11,000 volts is the more likely voltage required; load requirements will also decide. For pole lines, these voltages should be carried by conductors located on the topmost crossarms, and the arm or arms should preferably be painted a colour known to the linemen as being a known or/and a particular h.p. circuit—they thus serve as a visual reminder to linemen that they must be cautious when working on these poles. The secondary conductors can be carried on other coloured crossarms (or unpainted arms) and placed several feet below—depending on the voltage difference, type of construction, span, and size of conductors, etc. The kind and number of wires and/or conductors to be strung on a pole or frame are governed by the requirements of service and the solution of the technical problems involved.

For rural districts it is usually understood that such lines will be located at some distance from the main generating or distributing station or centre, and, if reasonable size or good practice is desired and an eye is kept on the future, all such rural lines can be constructed to afford good operating conditions and reduced maintenance expenses. Rural lines may call for just as high grade construction and standards of service as lines in urban and other areas. Hence, they should, because of their relative remoteness, etc., be built in accordance with good standard practice, and not merely to see how cheaply they can be constructed in applying too low factors of safety; "*cheaply*" constructed lines may cost both the undertakers and the customers more than well-built lines, where proper charges, etc. are applied for maintenance and depreciation and so forth. One of the best methods for reducing rural line cost, and whereby proper factors of safety may be maintained, is by proper increase of span-length (see p. 67). The arrangement of conductors should for every design and location be specially considered where trees are on the route. It may be cheaper and better to build a line with comparatively long spans supported on substantial poles than to use short spans and short poles. The kind of conductor material is of very great importance. The strength of a small-sized wood pole may decrease much more rapidly with age, etc. than the strength of a larger pole, and maintenance costs may be materially increased by the use of the small pole. For distribution work, in practically all cases it will be found cheaper and better in the long run to employ the more substantial pole. While the initial cost of poles can be kept down as low as possible (because of the great number involved), the construction of a given line should not increase maintenance and operating costs.

Designs, etc. are regulated by the Electricity Commissioners, and obligations are imposed on the undertakers; a few of the most important for the latter, and for this country at present, being:

> [1] (1) The declared pressure at the consumer's terminals must be constantly maintained within ∓ 4 per cent. for pressures up to 3000 volts.
>
> [1] (2) The declared pressure at the consumer's terminals must be constantly maintained within ∓ 12 per cent. in the case of pressures above 3000 volts.
>
> (3) The declared frequency must be maintained with a variation not exceeding ∓ 2·5 per cent.
>
> (4) The maintenance through each distributing main of a constant supply sufficient for the use of all the consumers entitled to be supplied from that main.
>
> [2] (5) The restriction of the area liable to interruption of supply, by suitable subdivision of the system of distributing mains.

Provided the requirements of voltage drop are met, the most desirable voltage is that which gives maximum overall economy of distribution. Within ordinary limits, the higher the voltage the cheaper a given size of line is per kVA transmitted, and the greater can be the spacing of sub-stations, etc. On the other hand, if the generating station is situated some distance from the load, rather than raise the distribution voltage it may prove more economical to have the primary line or the high-voltage transmission line feed directly all (or the larger) distributing centres, each of which may supply local h.p. distribution, or transformers direct, for distribution to individual consumers. The voltage must be high enough to ensure that the voltage variation at the boundaries of the distribution or the supply area can be kept within reasonable limits without excessive size and cost of feeders and so forth. It is usually desirable that the voltage variation should not exceed from 4 to 5 per cent. on either side of normal, or a total of 8 to 10 per cent., and from this 2 to 3 per cent. may be deducted for transformer voltage drop, leaving a permissible maximum drop in voltage of 6 to 8 per cent. in the high-pressure mains (see also p. 57). As a matter of fact, transformer drop *plus* generator

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[1] Unless otherwise specially sanctioned.

[2] A main for pressures above 3000 volts may not be used to transmit more than 1000 kW unless adequate provision is made for emergency supply in the event of breakdown of the main.

variations may exceed 4 per cent. without allowing for line drop. Apart from the size and length of conductor, the total drop depends largely on the class of load, and the power factor of the system is of great import (see also p. 100).

Distribution losses may be divided into:

Line losses.
Transformer losses.
Secondary main losses.
Service conductor losses.
Meter losses and errors.
Leakage losses and unaccounted-for losses.

These losses can be divided into loss of energy and loss of power at full load. The total energy loss consists of a loss independent of the amount of load, and includes core loss of transformers, the core loss excitation, loss in shunt coils of meters, and the loss proportional to the square of the current (I^2), including the copper losses of the transformers and the circuits, etc. For a lighting system, the full-load losses in the distribution system (including primary feeders, primary mains, transformers, secondary mains, service wires, and meters) may be as much as 16 per cent. of the power generated, and the daily energy loss about one-third of the energy generated, which would show an energy efficiency of about two-thirds, while the power capacity efficiency would, on these figures, show 84 per cent. These efficiencies, as also the efficiencies of any particular system of distribution, are gauged by the relative values of:

Load factor;
Power factor;
Shape of load curve;
Relation of transformer capacity to maximum load;
Diversity factor, etc.

✓ For any distribution system or circuit (whether underground or overhead) an important problem is that of permissible voltage drop, and the question of the most economical size of conductor for some cases becomes somewhat complicated, for the reason that the load which the cable or line has to carry is fixed by influences beyond the control of the designer, and all he can do is to provide a size to properly deal with the load. Once a line is put up, the endeavour usually is to load it up to its most economical loading. In distribution work, rarely is a size of cable or line put up to carry the total current at the moment of its installation—it is put up with a view to a growing load.

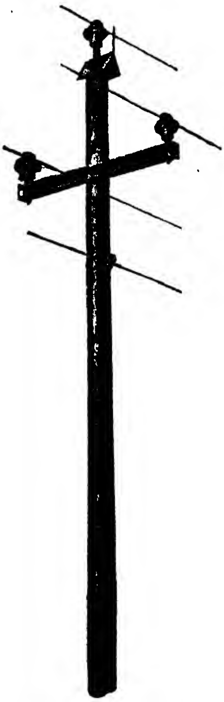

FIG. 7.—Showing a 3-wire circuit on wood pole, and the continuous earthed guard wire carried below this circuit (*Henley*). For better service and probably increased k V A capacity for equal voltage stress to earth (equal flashover value) and equal percentage voltage drop, change to the system shown in fig. 6.

For most lines—rural lines in particular—the most economic conductor section for a given load and loss is the object sought. That is to say, the economic conductor section for any given system means that for equal voltage strain to earth the size and weight of conductor is less for equal delivered load and loss, and therefore line-supports can be less in size and weight. The two most economic systems are the single-phase 3-wire with earthed neutral, and the three-phase 4-wire with earthed neutral. For a neutral conductor of, say, 60 per cent. the size of the outers, the three-phase 4-wire system has the advantage of usefulness over the single-phase 3-wire. For equal voltage from any line conductor to neutral, the three-phase 4-wire system permits of a smaller size of line (outer) conductors for equal percentage voltage drop than the single-phase 3-wire system. The single-phase 2-wire and the three-phase 3-wire systems for equal voltage strain to earth cannot be compared from an economic standpoint. Taken in their order of importance, the three most economic distribution systems are:

(1) The three-phase 4-wire earthed neutral. As compared with (2), this system has practically equal total sectional area of conductor, but the advantages of one less conductor (see p. 202).

(2) The two-phase 5-wire earthed neutral. As compared with (3), this system enjoys the polyphase advantages; also, as compared with (1), slightly less total sectional area of conductor is required, but considering all things it can be classed as second in importance (see p. 202).

(3) The single-phase 3-wire earthed neutral. This system requires slightly more total sectional area of conductor than (1), but has the advantage of one less conductor; it lacks the advantages of a polyphase system.

For each system the earthed neutral wire may or may not be carried on insulators. Where wooden poles are used, the writer very strongly recommends the retention of all possible insulation of the wood (*pole*+*crossarm*+pin), as this practice eliminates or decreases bird trouble, and it increases the flash-over value by a very large percentage above present practice in this country, and it also gives a better operating line.

As regards the different systems, broadly speaking, the direct-current system is best applied to densely loaded business and commercial zones of a town or city, but the low pressure at which direct-current circuits must be run limits the use of direct current to districts where the load is very much concentrated; hence, it is not discussed here.

The direct-current distribution system is simple and reliable, but economic and other requirements have long shown a necessity for the use of alternating-current distribution for wide and scattered loads, which fundamentally applies to supply by means of overhead lines.

Alternating-current distribution has the advantage over direct current, as transformer sub-stations or pole-stations are cheap (much cheaper and simpler and more efficient), and their use for lighting adds less to the cost per kW.H., and the alternating-current system is better and more economical where the load is scattered and relatively light, as in most rural areas. We thus have the most ideal distribution system, which permits of different voltages and loads to be tapped at any point, and permits the addition of supply feeders at various most suitable points, as determined by the particular distribution of (and/or) the load.

With reference to the primary systems, we have a choice of loop or radial feeders; the former feeders lead out from the station, describe a loop (as it were), and return again to the station. Loop feeders are usually provided with overload protection on each end where connected to station bus, and, in addition, station circuit-breakers are usually installed on each side of the points where taps to transformer installations are made in the load area; these are actuated by pilot wire or relay equipment so as to isolate automatically a faulty section between any two protection points, allowing the remainder of the loop to continue in service. Loop feeders are usually employed where the secondary network is omitted, or consists principally of ties between load points. On the 132,000-volt lines of the Central Electricity Board this method is being adopted. Loop feeders have the advantage of a minimum sacrifice of feeder and transformer capacity during trouble on one section of a feeder, but require primary circuit-breakers. When the secondary is in the form of a network, protection on the secondary side of transformers is necessary to prevent feed-back from the network through other transformers in case of trouble on a transformer or the feeder section.

As regards radial feeders, these are led out from the station to the load area where they may branch out further; they do not normally have primary connection with any other feeder, although tie-switches are sometimes required for emergency connections to adjoining feeders. Radial feeders are usually protected by overload circuit-breakers at the station, and may have simple forms of protection on the branches in the load area. Interconnected (interlaced) or paralleled radial feeders are used for supplying extensive low-voltage networks; they possess the advantage of simplicity and reliability in the isolation of trouble as well as ease of compensated voltage. And, in order to provide for service continuity on the secondary network in case of trouble in the primary, it is the practice to parallel or interlace two or more feeders, so that at least every alternate transformer can be fed from a different feeder. The amount of interconnection (interlacing) depends on the density and arrangement of load.

Without question, the a.c. distribution systems are the most suited to rural areas and for isolated and widely-scattered loads. Distribution for such areas might be arranged to have several primary feeds in parallel with a portion of the transformers having their h.p. windings connected to but one of the feeds, while the l.p. windings of all the transformers are connected to the secondary network; this of course depends on whether the area is a sufficiently satisfactory one from the undertakers' standpoint. The primary feeders would be connected radially in certain instances, while in other differently shaped load areas, or under other local conditions, the loop system would be used.

The simpler radial system may consist of duplicate feeders direct from the generating station (h.p. or e.h.p.) sub-station, to each sub-station, equipped with time-limit overloads at the former or source end, and reverse power relays at the latter or receiver sub-station end. This limits the risk of interruptions to the sub-station fed by the faulty feeder, but, owing to defects in protection arrangements, it would not ensure complete continuity of supply. The more complicated interconnected (interlaced or paralleled) radial system is one in which all the mains and sub-stations are connected together; thus, duplicate supply can be given to the economical method of ring mains. This is the method now commonly used in underground distribution in this country, and referred to as correct practice. For such a system to operate satisfactorily, it is essential that each section be so protected that a faulty section is isolated instantaneously without serious shock to the rest of the system and without disconnecting other circuits. The leading manufacturers make and supply the desired protective gear and apparatus; their methods of operation need not be mentioned here, as they have been discussed repeatedly in makers' and current literature. The above also includes pilot wire schemes.

In dealing with an extensive area, 11,000 to 33,000 volts will be chosen. These main lines will pass through or near villages, and local supplies will be taken off and the voltage stepped down for local rural lines, which may be single-phase or the combination three-phase 4-wire for power and light. The rural distribution system may be anything from 400 to 11,000 volts, depending on the size of, and load in, the district. In certain cases the 132,000-volt main transmission line may be tapped for 33,000-volt main distribution purposes—this does not involve any special knowledge or practice.

For three-phase distribution, in the case of h.p. not exceeding 3300 volts between phases, the methods adopted are, in general, similar to those for l.p., with the exception that each individual supply is usually controlled by an automatic oil-switch equipped with an instantaneous protective tripping device in addition to overload protection. In low- or medium-pressure distribution, the maximum pressure between any pair of conductors does not in general practice normally exceed 440 volts, and they are used for general distribution to the smaller consumers for small motor installations up to about 100 H.P.

Due to the growth of electric supply undertakings, for some years past the tendency has been to supply from sub-stations, which are themselves supplied from a more extensive high- or extra high-pressure network. This presents an important influence on distribution design as, within limits, the number of sub-stations (transformer points) can be easily increased; this can also be done without the necessity of putting up more lines or circuits, and the maximum distance of feed can also be kept sufficiently low to enable the line or circuits to be run at their most economical loading. As there is practically no limit to the number of transformer stations which can be installed, the secondary (l.p.) network need not necessarily be extensive, and the network can be of the simplest type, and it may require but one or two sizes of conductor practically throughout which would also facilitate subdivision as the load grows; a 0·05 sq. in. copper cable would be probably the smallest size for a main.

In the case of secondary systems where both power and lighting loads are present in considerable quantity, and both well distributed over the area, the necessity of a polyphase secondary (preferably three-phase 4-wire) main for both services is obvious because of its advantages over two separate systems or circuits. Some of the advantages are:

Reduction in total sectional area of conductor necessary;
Reduction in number of conductors, insulators, and line materials;
Reduction in the size of line-support;
Reduction in number of transformers, cut-outs, etc.;
Reduction in total transformer capacity on account of diversity between loads;
Reduction in number of service wires to consumers;
Neater and better-looking line;
Obtain better diversity between power and lighting loads;
Can give single-phase and polyphase service to all consumers from one polyphase circuit.

In the transmission of energy in bulk, three-phase is more economical and more useful than single-phase; this being the chief reason why it is so universally used. For lighting, ordinary domestic heating in general, and for relatively small motors, the single-phase distribution is economical and efficient, and transformers and switch-gear are cheaper. The great economy in conductor has lead to the use of the three-phase system instead of the 2-wire system for low-pressure circuits, except where a relatively small amount of power is to be transmitted, or the receiver voltage is greater than 230 volts for lighting. The distance to which power can be transmitted with the same loss, same receiver voltage, and same weight of conductors, is increased 62·5 per cent. by the use of a three-phase system with the neutral of the same size as the outside conductors. The increased distance to which power can be transmitted from a transformer with a 3-wire secondary as compared with one having a 2-wire secondary and the same receiver voltage, usually makes it possible to connect all the consumers in the area of two or three street-blocks (assuming a residential area) to one transformer, with a reduction in the transformer capacity to less than one-half what it would be if each consumer were supplied with a separate transformer. It is advisable, where possible, to interconnect the secondary circuits of the adjacent transformers, so that they will aid each other when the maximum load does not come on transformers at the same time; when this practice is followed, the secondary of each transformer should be fused (see also p. 196).

For a 3-wire single-phase system it is important that the load be divided almost equally between the two sides of the system at all times, as the regulation of each side is dependent upon the load on the other. If the two sides were equally loaded and the load should be thrown off one side, the voltage on the other side may fall an amount equal to the difference between the supply voltage and the receiver voltage when the load was equal on the two sides, and perhaps rise to almost twice this amount on the side from which the load was removed. The load is usually kept balanced within 10 per cent., which can be accomplished by wiring each consumer's premises on the single-phase 3-wire system and distributing the load as equally as possible. The centre point of the transformer winding should preferably be permanently earthed, thereby reducing the voltage from outer conductor to earth to

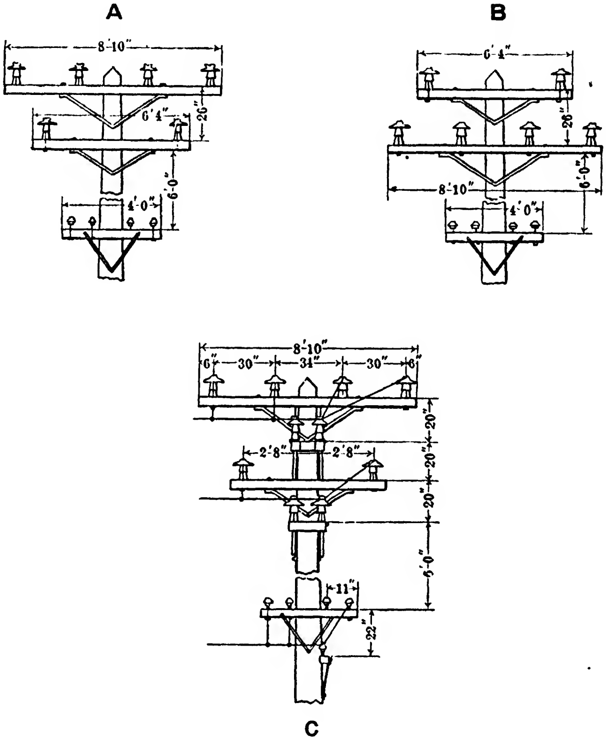

Fig. 8.—Showing 11,000 volt primary distribution line with joint occupancy; (A) and (B) for straight line, and (C) for street corner.

50 per cent. that between the two outers, and in so doing placing single-phase transmission almost on a par with three-phase in the matter of economy of conductors. It is necessary to note that, when the secondary winding is *properly* interlaced, 50 per cent. unbalance load can be taken from the middle lead and either side lead without causing serious unbalance of voltage.

For simplicity of system outlay, and best system voltage balance, etc. the three-phase 4-wire secondary system, with single-phase load star connected on all three phases, has advantages over all other systems or schemes. This usually employs three-phase transformer installations on which the load and the voltage can be very closely balanced, and balance on the primary feeders follows. Four-wire secondary is used. Some of the advantages of this system arise from the fact that the voltage to neutral, on which the single-phase load is carried, is 57·7 per cent. of the three-phase voltage between phases, but any two single-phase voltages are not in phase, and therefore require two single-phase or one polyphase meter where a 3-wire service is required, and is tapped across any two of the three phases. For distributing at primary and secondary voltages, the three-phase 4-wire system is the best one to adopt, because it fulfils practically all the requirements of a distribution system, such as:

Reliability.
Safety.
Economy of line-support and underground duct space.
It provides the greatest capacity for a given investment.
It can be adopted to meet all of the conditions of central station service, so that load of any character may be attached to a single distributing system, allowing it to enjoy all the advantages of diversity factor.
Low operating and maintenance costs.
It can start out of any district (rural or urban not yet served) as a single-phase 2-wire (or 3-wire) system, since it is capable of supplying domestic consumers and street lighting with all the investment of a permanent character, and later, when the load increases sufficiently, two (or one) more conductors may be added to care for the load as the territory is developed, thus enabling a common system to serve an entire district or area irrespective of the character of load.

The three-phase 4-wire system makes use of a neutral conductor which serves the same purpose as the neutral of the single-phase system, and carries no current as long as the load is balanced among the phases. The line voltage can be 173 per cent. that of the three-phase 3-wire system, which accounts for the decrease in the weight of the conductors. It is the cheapest system to install and is largely used in mills and works where the load consists principally of three-phase motors, for, by using 230 volts for lighting and 400 volts for motors, the advantages of a high-motor voltage can be obtained without the use of other transformers for the lighting load, and single-phase 3-wire advantages can be obtained for lighting. The same system may be used for the primary distribution circuits without introducing much more complication than the three-phase 3-wire system requires (see fig. 32).

In some cases it is necessary to change from delta to star-connection of the transformers. In this way we may raise the distribution voltage and retain the same transformers and consumers' installations, including equipment, etc. by earthing the neutral, and by running a fourth conductor and connecting the transformer between neutral and the line conductors instead of between line conductors. In this way existing circuits can be operated at 73 per cent. higher voltage, using the same transformer, and in some instances the same line insulators. If the voltage is higher than 11,000 volts, transformer failure may occur —the determining factor in this respect is the kind of construction used and the degree to which the earthing of the neutral approaches a dead earth *throughout* (see p. 200). Also, as the maximum possible short-circuit kVA in a line increases as the square of the voltage (E^2), the rupturing capacity of the fuses and circuit-breakers requires careful consideration. By adopting the kind of construction proposed, there is no necessity to change the insulators.

As a substitute, where single-phase transformers are used in place of a three-phase unit, we may operate on two of the three phases and the neutral. Such a connection (star 4-wire one side and open delta other side) will give satisfactory service for the operation of three-phase induction motors of any size, but the total capacity of the two transformers is now only 86·6 per cent. of their true rated capacity. The effective rating of the two transformers is but 57 per cent. of the total *original* rating. Due to the unbalanced impedances, the voltage drop is unsymmetrical, and will cause a slight unbalance in the full-load voltages. This connection is a good substitute and is a desirable connection in many cases, as the cost of a two-transformer installation is less than a three transformer, and it is sometimes necessary to use it temporarily in case of burn-out of a phase unit, and where another single-phase transformer is not available at the time (see fig. 32).

In making calculations for determining stresses in the line supports where conditions as to height, length of span, loading, etc. are fairly uniform, it is usually unnecessary to calculate each span separately in order to obtain results which are as nearly as exact as the various assumptions which must be made. This is also evident from the fact that the tensions in the conductors throughout the length of a wood-pole line tend to equalise themselves when they are installed, and for such conditions it is considered sufficiently accurate to employ an average span as the basis for strength calculations.

The factor of safety for (red fir) wood poles is specified as 3·5 at the present time—it was previously 10·0. This apparent large difference is not so great as might be expected at first sight; nevertheless, if it be of a *fixed value* (and it is) for all districts and all places (locations) and all grades of lines (h.t., e.h.t., l.t., insignificant as well as very important lines), then there is something wrong somewhere. However, let us take an example for the purpose of showing how the size of a pole is affected by a change in the factor of safety, F. Take the example given on p. 85 and assume that a factor of safety, F, of 3·5 has already been allowed; then, total bending moment is 175,000/3·5 = 50,000 ft.-lb., which represents the actual calculated figures. Hence, for different factors of safety which are, and which have been, in use, we obtain the following relations:

(F).	(M).	(*d*).	Difference in (*d*).
10·0	500,000	19·75 inches.	141 per cent.
8·0	400,000	18·50 ,,	132 ,,
7·0	350,000	17·50 ,,	125 ,,
6·0	300,000	16·75 ,,	119 ,,
5·0	250,000	15·75 ,,	112 ,,
3·5	175,000	14·00 ,,	100 ,,
2·0	100,000	11·50 ,,	82 ,,
1·0	50,000	9·25 ,,	66 ,,

Thus, by doubling the factor of safety we increase the diameter, d, of a pole 25 per cent.; that is, for $F = 3·5$ we have $d = 14·0$, and for $F = 7·0$, we have

$$14·0 + 25 \text{ per cent.} = 14·0 + 3·5 = 17·5 \text{ in.}$$

In attempting to arrive at a proper value for the ultimate strength of wood in poles, numerous experiments have been made from time to time. From the information available the *maximum* fibre stress is given to us, but the *allowable* fibre stress is varied at different times, which still indicates lack of knowledge. Obviously, a figure somewhat lower than the average value of the breaking strength for a given timber and kind of pole is taken in order to ensure that the very large majority of poles come within the assumed average strength when divided by the factor of safety we are to use.

For distribution work in particular, many lines do not require at the time of their construction a particularly heavy grade of construction, but owing to expectation of added conductor or circuits they are, or should be, designed to conform to known or anticipated future requirements. If not provided for, the line will be expensive to rebuild to meet the requirements of additions to be made, and therefore distribution lines should be originally constructed to meet the requirements of the future, not solely for the present.

Calculations of stresses are made on the assumption that there is no deflection of the supports. With wood poles deflections do occur, and they tend to relieve local strains and distribute the load more uniformly; the conductors themselves also exert an important influence in distributing the load along the line by facilitating the support of the weaker by the stronger poles. In wood-pole lines each pole assists materially in supporting those adjacent to it, for the reason that the conductors themselves act as stays after the pole has deflected to a certain extent. This principle can be utilised in wood-pole lines subjected to heavy gusts of wind which are not uniformly distributed over the length of line. A longitudinal stay at such places helps to stiffen the line and distribute local loads over several poles. Due to the greater flexibility of a wood-pole line it will be subjected to much less ice and snow accumulation than a lattice steel-pole line, hence the *loading conditions* for wood-pole lines should be lighter (less) than steel-pole lines, *i.e.* $\frac{3}{16}$-in. ice for the former and $\frac{1}{4}$-in. ice for the latter. This is due to changing temperature, etc. and relatively shorter spans and greater movement of the conductors, etc. of the wood-pole line.

The strength of wood poles should be based on ground-line diameter, because when a pole is first installed it should have much excess strength, but the ground-line soon becomes (through decay) the weakest section of the pole, or the point where failure is most likely to occur. Where poles have slight tapers the weakest section is always near the ground-line, while for poles having excessive tapers the weakest section is initially at some distance above the ground-line. Nevertheless, the ground-line section should always be taken as the weakest section of a pole.

As regards the strength of steel poles and structures, the allowable stress for tension, based on the ultimate strength and elastic limit, are not given in this country. The tensile stress is relatively of little importance in the design of steel structures, because the important members, including the legs, are subject to either compression or tension, according to the circumstances, and when properly designed for compression will invariably be found sufficiently strong in tension. Steel and iron parts are subject to deterioration unless properly protected by galvanising or some other equally effective treatment,[1] or unless a good coat of graphite or other weatherproof paint is maintained. Extra thickness is prescribed for painted members as compared with galvanised members, and is justified on the ground that painted steel deteriorates, more especially in places where the sulphur from coal smoke has a particularly injurious effect.

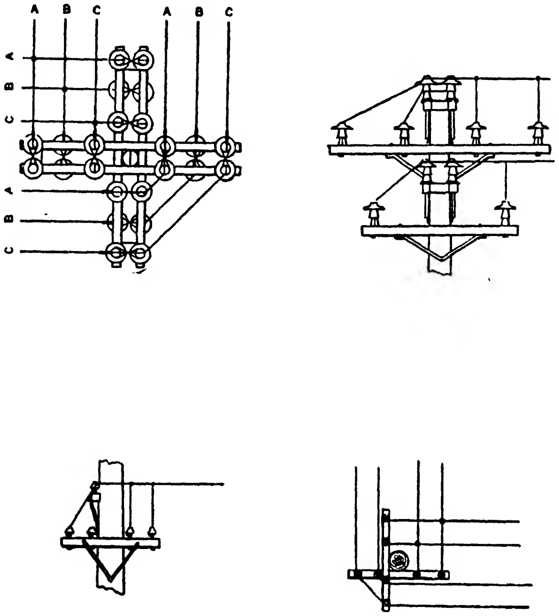

FIG. 8a.—Showing methods of construction and taking 90° angle for high-voltage 3-phase, and low-voltage single-phase lines.

(The attachment of an uninsulated stay to a wooden pole has

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[1] See *Metal Spraying*, by T. H. Turner and W. F. Budgen. London: C. Griffin & Co., Ltd., 42 Drury Lane, W.C. 2.

the effect of bringing the earth up the pole and reducing the length of the wood pole, which may be depended upon for valuable *insulation*. Such stays are also a danger to linemen, just as much as is the continuous earthed guard wire, for they may come directly into contact with them and a live conductor at the same time. Suitable insulators, properly located, should be installed in the stay to afford protection to the pole, to the lineman, and to the pedestrian (see p. 62). Where secondary mains only are strung there is a necessity from the insulation view-point for installing insulators in stays. It is the general custom to install stay-insulators on lines where the voltages range from between about 240 to 20,000 volts. On wood poles they should be installed for voltages at and lower than 240 volts because of retaining the insulation of the wood, and because it is around this voltage that the greatest benefits, etc. are derived. They are not (but should be) installed in stays on lines operating at voltages over 20,000 volts; they have not been installed because, with present practice, they have not been given proper maintenance, and the more dependable alternative has been to earth the stays thoroughly (see p. 165). The stay insulator should be somewhat stronger than the stay, because a stay with a thimble may be used which will distribute the mechanical stresses in the insulator in a way differing from that for which it was designed, and this might cause its failure; if so, it should have a clearance from ground of at least 8 ft. after it has dropped vertically. If a stay is attached to a pole, such as a wood pole of the smaller size (light-weight class) capable of considerable deflection, the stay is likely to fail before the pole could deflect enough to take any or much of the load, and thus should be strong enough to take the total load imposed upon the pole. All stays when installed properly are under initial stress, and may fail before stretching enough to put much load on the wood poles; hence, the strength of a pole may not aid a stay, so that the stay must take the total load or it may be ineffective. Thimbles should be used on stays when they are attached to anchor rods, for by so doing the point of application of the load can be distributed in the conductor. Stays should be prevented from cutting into the wood or slipping, and thus slacking the stay and causing it to become ineffective (see fig. 24).

If more attention were given to the right kind of ground for a stay-anchor, so that it is effectively earthed, there would be less trouble from leakage current over the stays; that is to say, there would be less danger from shocks. The neutral conductor may be used for earthing the stays. In addition to a low resistance, the stay cable (commonly called "wire," which is an error, as a stay should always be stranded) should have a stay-insulator. The approximate dry flash-over voltage of a stay-insulator for different voltage lines is:

Normal Line Voltage.	*Minimum* Dry Flash-over of Stay Insulator.
132,000	200,000
110,000	150,000
66,000	100,000
33,000	50,000
22,000	35,000
11,000	20,000
6600	15,000
3300	10,000
400	3,300

The function of any insulator is to prevent a loss of energy by conduction between conductors and from conductor and earth, and also to act as a good mechanical support. Its manufacture has little concern for the operating engineer; his chief attention centres around its effectiveness in service and its operating characteristics. In practice the insulator has imposed upon it a requirement of reliability and continuous service that no other element of the transmission and distribution system has to meet, and the climatic conditions, the construction, and the safety standards of this country are very hard on insulation.

Many failures have been due to mechanical stresses set up by the unequal expansion of the various elements of the unit, and experience has shown that insulators in service, and in certain districts in particular, may fail on account of the great variations in the atmospheric temperature, which cause minute cracks to appear in the porcelain, and ultimately cause the failure of the insulator; many failures are due to the kind of construction. In practice it has also been found that many pin-type insulators failed because the insulator had been screwed down too tightly on the pin, so that expansion and contraction finally split the insulator. Line failures and depreciation of insulators can also be traced to improper line location. Excluding the effects of construction standards such as shown in fig. 7, in so far as concerns the location and its effect on the insulation, the rate of depreciation for a given working voltage and system will, as a general rule, be somewhat in the following order:

The highest where the line is located along the sea coast, in or very near certain chemical or cement works, and in railway yards, etc.;

The next will be in hilly districts, in high altitudes, also where soot, smoke, fog, dirt, and cement dust are prevalent, and

Least where the line crosses cultivated territory and subjected to clear and clean atmosphere.

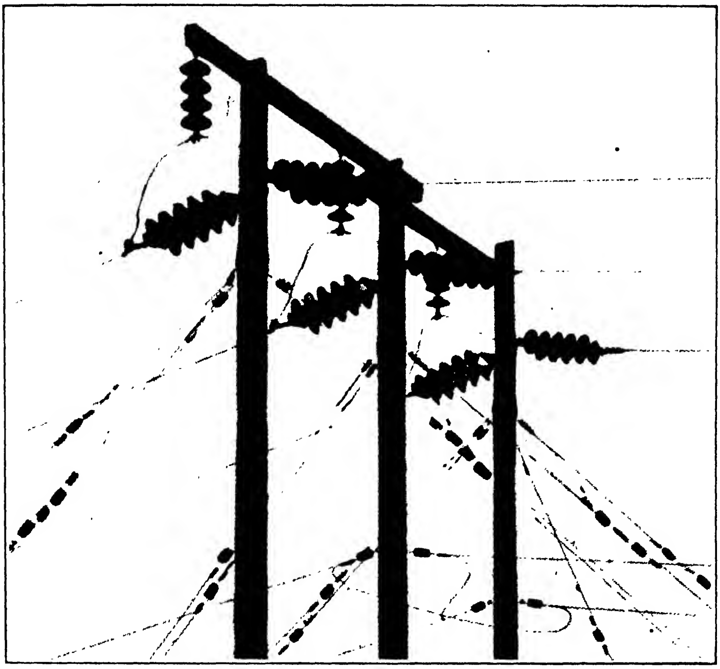


FIG. 9.—66,000-volt wood-pole line construction, showing method at dead-end or anchor support (using three poles); method of insulating the stay-wires, and method of transposing the telephone line, using 6600-volt insulators. Each stay insulator is approximately 22,000 lb. strength, and subjected to a dry flash-over voltage of 55,000.

The maximum stress acts on the conductor at the insulator when the temperature is a minimum, and when at the same time the conductor is carrying its maximum load. This maximum stress usually occurs when the insulation value of the construction (with continual wet weather, and continuous earthed wire, earthed pin, earthed arm, earthed pole, etc.) is at its lowest; this is always so with the present practice of this country. Independent of the size, form, and mass of porcelain, line insulation can be increased in several ways, some of which are:

By employing the insulator best suited to the particular climate and atmosphere;

Having the poles traverse a route offering high-earth resistance, with clean atmosphere;

Employing supports offering high resistance in themselves;

Following the principle of keeping a moderate height, avoiding known lightning paths, and keeping away from iron and other metallic surface deposits and formations;

Not taking the earth up to the insulator pin or up, and in contact with, the pole at all;

Employing the horizontal arrangement of conductors;

Choosing a mean length of span, and, in lightning areas, avoiding long spans in order to keep the conductors low;

Properly earthing the neutral point of the system;

If an overhead earth-wire is used (a practice not in the ordinary way recommended by the author for wood-pole construction, unless according to fig. 6), insulate it from the poles.

Most line troubles which have been attributed to electrical disturbances were actually due to faulty line insulation. Line insulators are required to withstand a mechanical stress equal to at least the elastic limit of the conductor when erected in any direction in a plane perpendicular to the axis of the pin. They should be chosen to withstand:

The total wind pressure acting on the conductor, and any other transverse force produced by a change in direction of the line;

The total weight of conductor, including vertical wind pressure and ice-loads;

The longitudinal stress occasioned by the breaking of the conductor.

Pole-top extensions have proved very effective. If the pole is strong enough, pole-top extensions may permit greater length of span and a saving in insulators and their hazards. And, for a three-phase circuit, where sufficient height can be obtained by placing the top insulator well above the top of the pole, the construction is simplified and the electrical characteristics improved.

Based simply on a common-sense principle, there should be a general practice requiring that:

High-pressure conductors be placed above medium- and low-pressure conductors; or

High-pressure conductors be placed on a level (when approved) with medium-pressure conductors.

And:

Extra high-pressure conductors be placed above high-pressure conductors; or

Extra high-pressure conductors be placed on a level (when approved) with high-pressure conductors;

Medium- and low-pressure conductors might be placed on a level with extra high-pressure conductors, but never above;

Telephone and telegraph wires not to be placed above, nor on a level with, high-pressure and extra high-pressure conductors.

With respect to the arrangement of conductors on the poles, the following methods mentioned indicate ordinary common-sense principles:

Have the heaviest conductors placed on the lowest crossarms in order to reduce the bending stress on the pole to a minimum (see p. 54);

Place the heaviest conductors on the pins next to the pole in order to reduce the bending stress on the crossarm to a minimum;

Arrange the conductors of each circuit as close together as practicable (on adjacent pins), in order to reduce the self-induction of the circuit;

Arrange the conductors of different circuits as far apart as practicable in order to reduce their mutual-induction;

Have the highest voltage circuits placed on the topmost arm and on the pins farmost from the pole in order to reduce the danger to linemen, etc.;

Arrange the circuits or conductors as symmetrically as practicable on the two sides of the pole; especially those which end at the pole, in order to reduce the twisting stress on the pole to a minimum;

Have the arrangement of conductors symmetrical throughout—this is essential for safe and economical operation, also for neatness;

Have the secondary main on the lower crossarms or on racks, in order to reduce danger of accidental crossings, etc.;

For a three-phase 3-wire circuit, and for best electrical performance, arrange conductors in the form of an equilateral triangle in order to render the inductances practically equal.

At crossings such as highways and railways, conditions usually alter the method of construction. The various methods available for such crossings are:

Use extra crossarms; and
Insulators in series or in parallel, or both;
Use strong strain insulators; and/or
Employ shorter spans;
Use double pole-fixtures; and/or
Use stronger poles or frames; and/or
Use extra high poles;
Employ guard wires, preferably of a simple form; or
Employ double wires (conductors) with messenger cable;
In special cases use earthed network of iron; and
In special cases use truss bridge across railway tracts;
In general, place telegraph or telephone lines underground (in every case place them *below* power conductors); and
Employ guard wires over telegraph or telephone lines;
Employ higher strength conductors; and/or
Make use of slack span and dead-ends.

By placing primary conductors at one side (one end) of the crossarm, and the secondary conductors at the other end of the same crossarm, it is possible to use a pole of several feet less in height (in overall length) than would be necessary if primary conductors were placed above the secondary conductors. Apart from this, safer construction is provided in that the primary conductors would not, should they fall, come into contact with the secondary conductors.

It is desirable from the standpoint of the linemen, and in order to get better and more rapid work in times of line trouble, to have the circuits of higher voltage on a pole at the highest level, and where there are circuits of a number of different voltages on a pole, to arrange them in order of voltage with the highest voltage at the top. The lowest voltage circuit will usually be worked on more frequently than the circuits of higher voltages, and the construction should be such as will permit work without coming into proximity with the high-voltage conductors, and also necessitate less climbing. It is much safer to climb through conductors operating at low voltages to work on the high-voltage conductors than *vice versa*. The advantages of having the higher above the lesser voltage lines should be evident to all engineers.

In the stringing of *secondary* conductors the following precautions should be observed:

They may be located on crossarm, or on racks below the lowest arm carrying the primary conductors; the wooden arm provides a better insulated line;

Conductors of the same circuit may be carried on adjacent pins (where used), and so located that when service-loops are run, the crossing of the pole may be avoided as much as possible;

When running mains where there is a probability of a change in the system requiring additional conductors (such as that of developing a new area), it is desirable to so locate the conductors that vacant pins will be left which will permit of the running of the additional conductors without disturbing the existing circuit or circuits;

When running single-phase 2-wire mains, the conductors may be placed on the two end pins on the side nearer the greatest number of consumers;

When running a single-phase 3-wire main, the conductors may be placed on the three end pins nearer the greater number of consumers, with the neutral conductor either on the outside or in the centre;

When running a three-phase 3-wire main, the conductors may be placed on the three end pins nearer the greatest number of consumers;

When running a three-phase 4-wire circuit, the conductors may be placed on the four end pins nearest the greatest number of consumers, with the neutral conductor on the outside for simplicity for taps and as a protective measure in case of a broken primary conductor. In this way the neutral conductor may be a better guard than that where the top conductor of the secondary rack arrangement is the neutral. The neutral may be carried on the *road* side or on the *tree* side as found best.

Rack construction has its best field of usefulness in residence-lighting districts where line construction, consisting of a few wires, must be the simplest. Where both light and power secondaries are necessary, there is no advantage over crossarm construction as, apart from the resulting decrease in insulation, climbing space is taken up, also other important matters are involved, especially at corners.

Because of lack of vertical space on a pole (or the necessity for stringing additional conductors) it may be impossible to put up more crossarms, and at the same time provide proper separation vertically between conductors of the same size, or of different classifications of construction or/and voltages. Conductors of different sizes have different sags on the same supports, but the smaller conductors will have about the same ultimate sag under full ice-load whether initially strung with the small sag or not, while the larger conductors will increase their sags comparatively little with the ice-load and wind. Therefore, larger sags for large conductors can be allowed (greater than would be necessary if their strengths alone were considered) in order that the smaller conductors if placed above them, as is sometimes done, can be given sufficiently large initial sags to keep moderate the variation of sag under increased load. Where heavy feeders are run on the same poles with other conductors, they should preferably occupy the lower crossarm, because an excessive sag will not reduce but rather increase conductor clearances.

It is good policy to have conductor separations depend on voltage, sag, and size of conductor for a given conductor metal. Separations and clearances should be determined by the highest voltage concerned; this is evident from the fact that hazards depend somewhat on the voltage, and clearances should be governed accordingly (see p. 61).

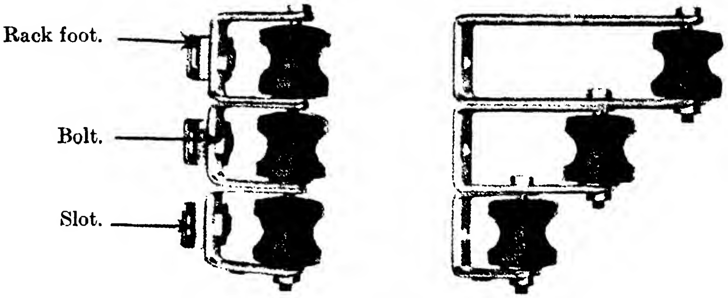


FIG. 10.—Type of racks for secondary lines.

It is customary to install low-voltage secondary conductors on racks attached directly to the poles; the wood arm is, of course, a better insulated line. Such construction may facilitate the connection of services and of branches, and may simplify the wiring on poles. However, the climbing space cannot be maintained continually on one side of the pole. It is therefore necessary to supply sufficient lateral working space both above (between h.p. and l.p.) and below the racks to permit the linemen to get around them. Placing secondary mains on vertical racks practically cuts the climbing space in half, and, while such construction provides comparatively simple methods for attachment of service taps, it requires readjustment of other construction to avoid obstructing space for making repairs, and, unless made, this method constitutes a hazard. For a few conductors, rack construction is recommended, but, where two or more circuits are involved, liberal clearances and space cannot often be given. Restricted or reduced clearances greatly increase hazards.

Thus, in the place of crossarms we may make use of the rack construction. This type of construction for secondary lines has certain advantages, some of which are:

> The neutral conductor can be placed on the top spool of the rack, to protect the lower conductors from a falling primary conductor;
>
> It offers a vertical uniform system of distribution;
>
> It may offer a neater-looking appearance (see fig. 10).

To avoid certain possible trouble from these racks the conductors can be tied on the outside of the insulators, *i.e.* on the side away from the pole. If the conductors are tied in this way, a loose conductor may fall free of the rack, and it may be supported by adjacent poles. If racks are used for crossings, at angles, or where clearance is small, the inside tie would probably be desirable.

Placing the neutral above the phase conductors may result in a more dangerous line, since the earthed neutral conductor has no benefit from the rise in temperature due to the current flow which the phase conductors have; it has relatively greater mechanical overload as well as unequal and greater sag, assuming equal size of conductors; also, the tendency of ice-coating is to fall off the phase conductors first. If the neutral conductor is placed above the phase conductors it should be given a slightly greater sag, or, failing this, due to restricted overhead clearance (see p. 130), copper alloy conductor can with advantage be used for the neutral, because it is stronger and safer and requires less sag, etc.

The power-line conductor (not a communication wire) is very rarely the weakest link; the tension in the conductor is not proportional to the total loading as is the case with its supports, *i.e.* the poles, insulators, and pins, which are more or less rigid.

Overhead conductors for low- and medium-voltage distribution lines are generally covered with weatherproof double or triple braid. Double braid is suitable for line voltages of 600 maximum, and triple braid for voltages up to about 2500. The chief object of this covering is for the purpose of limiting the short-circuit current due to an accidental cross or earthing. Rubber coverings are not generally used because of the expense, their rapid deterioration, and the impossibility of maintaining the insulation for very long. Bare conductor is generally used on circuits operating at

6600 volts and above, to avoid giving a false sense of security, and for economy.

Sometimes a rubber-covered conductor is used consisting of copper covered with rubber-filled tape, then a serving of jute thoroughly saturated with tar, followed by further tape, then over this tape is a thoroughly weatherproof cotton braid. This conductor often prevents trouble from short circuits, swinging earths, and leakage-current losses.

In making comparisons of copper (where area = 1·0) and aluminium (where area = 1·64), it should be kept in mind that the aluminium conductor offers more surface to the wind—for equal conductivity—and this, combined with its lower tensile strength and greater coefficient of expansion, means increased sag and greater horizontal loading, and consequently may require a higher and a stronger pole; in other words, poles have to be higher and the crossarms longer, and both have to withstand increased loads (see p. 111, also Chapter IV. of author's book, *Overhead Electric Power Transmission Engineering*).

TABLE I.

COMPARATIVE TABLE OF WIRE GAUGE.

(See Table for Latest Solid Wire Standard.)

Gauge No.	British Standard Gauge (S.W.G. or L.S.G.).		American Gauge (A.W.G. or B. & S.).	
	Diameter, Inch.	Square Inch.	Diameter, Inch.	Square Inch.
7/0	0·500	0·1964		
6/0	0·464	0·1691	0·5800	0·2642
5/0	0·432	0·1466	0·5165	0·2095
4/0	0·400	0·1257	0·4600	0·1662
3/0	0·372	0·1087	0·4096	0·1318
2/0	0·348	0·0951	0·3648	0·1045
1/0	0·324	0·0825	0·3249	0·0829
1	0·300	0·0707	0·2893	0·0657
2	0·276	0·0598	0·2576	0·0521
3	0·252	0·0499	0·2294	0·0413
4	0·232	0·0423	0·2043	0·0328
5	0·212	0·0353	0·1819	0·0260
6	0·192	0·0289	0·1620	0·0206
7	0·176	0·0243	0·1443	0·0163
8	0·160	0·0201	0·1285	0·0130

In distribution work the size of conductors depends upon the voltage drop permissible, when proper consideration has been given to the *probable growth* of the load. In ordinary practice the following values are fairly representative for lighting:

Circuit.	Approximate Average Percentage Volts Drop.
Primary feeders	10
Primary mains	5
Secondary transformers	2
Secondary mains	5
Service leads	1
Consumers' wiring	2

Note.—The primary-feeder drop is usually taken care of by voltage regulators at the station.

According to regulations (for this country) a distributor has to work within 4 or 5 per cent. voltage drop. For rural work in particular, where lines are longer and one or more transformers are in circuit, 4 per cent. is certainly too low. The total voltage drop would be more like 5 per cent. for lighting circuits and up to 10 per cent. for power circuits, which is not unreasonable; this total volts drop would be split up approximately as follows:

Circuits.	(Lighting.)	(Power.)
In feeders	2·5 per cent.	6·0 per cent.
In mains	1·0 ,,	2·0 ,,
In services	1·5 ,,	2·0 ,,
Total volts drop	5·0 ,,	10·0 ,,

In general practice the maximum variation of voltage is about as follows:

Lamps on a lighting distribution not to exceed (above or below normal) . . 1·5 to 3 per cent.

and

Motors on a power distribution not to exceed (above or below normal) . . 3·5 to 6 per cent.

(1 per cent. decrease in voltage on the motor decreases the torque about 2 per cent., and 1 per cent. increase on the motor increases the magnetising current by the same amount; starting torque varies approximately as E^2).

The IR drop for a given current, I, depends almost entirely on the conductor material, its size, length, and the temperature. On the other hand, the IZ drop for a given current, I, depends not only on the same conditions but it varies with the conductor spacing and disposition, the system frequency, and the load power factor. Of still further importance is the percentage voltage drop, which varies inversely as the line voltage (E^2) for a given load, distance, and size of conductor; also, the sectional area of conductor varies inversely as E^2 for a given load, distance, and loss. And, for constant (or for unity) power factor, and constant load (kW or kVA), the percentage voltage drop varies inversely as E^2, —that is, e per cent. $= (100{,}000PZ)/E^2 \cos \phi$. However, for equal maximum voltage with regard to earth (see p. 99), apart from a knowledge of the amount of copper required, we often desire to know the relative kW load we can deliver over a line. This is given in Table II. (see page 59).

The separation of conductors is usually understood to mean separation in a horizontal plane. The minimum horizontal separation is dependent upon the following conditions:

The line voltage;
Disposition or arrangement of conductors;
Number of conductors on the pole;
Kind of conductor metal;
Whether pole, frame, or structure is used;
Type of frame or structure;
Sag of conductors;
Length of span;
The amount and direction of wind taken (or not taken) as basis for loading;
Total loading requirements;
Type of insulator used;
Whether on straight line, corner, crossing, etc.;
Whether at sea-level or very high altitude;
The system—whether earthed or otherwise.
(See also p. 156 for horizontal *versus* vertical arrangements.)

Some of the more common conductor arrangements are shown on page 60.

(A) This arrangement permits of a longer span between line supports, or of less spacing of the line conductors for equal span-length than with conductors arranged as shown in (C) or (D). It also has the advantage of minimum inductive reactance. A greater distance may be used between conductors than for (E),

TABLE II.

CONSTANTS AND FORMULÆ FOR INSULATED COPPER CABLES AND ORDINARY UNDERGROUND (OR OVERHEAD) DISTRIBUTION NETWORK.

System.	Voltage.	Ohmic Volts. Volts Drop.	Current in Amperes.	Sectional Area in Square Inch.	Impedance Volts. Voltage Drop between Phases.	Impedance Volts. Total Volts Drop in per Cent.	Kilowatts Transmitted.
Three-phase—							
4-wire	$\sqrt{3}E$	$\sqrt{3}IRt$	$\frac{1000P}{3E \cos\phi}$	$\frac{0{\cdot}282Pl}{E^2e' \cos\phi}$	$\sqrt{3}IZt$	$\frac{IZt}{E}100$	$\frac{3EI \cos\phi}{1000}$
3-wire	E	$\sqrt{3}IRt$	$\frac{1000P}{\sqrt{3}E \cos\phi}$	$\frac{0{\cdot}846Pl}{E^2e' \cos\phi}$	$\sqrt{3}IZt$	$\frac{\sqrt{3}IZt}{E}100$	$\frac{\sqrt{3}EI \cos\phi}{1000}$
Quarter-phase[1]—							
5-wire	2E	2IRt	$\frac{1000P}{4E \cos\phi}$	$\frac{0{\cdot}212Pl}{E^2e' \cos\phi}$	2IZt	$\frac{IZt}{E}100$	$\frac{4EI \cos\phi}{1000}$
Two-phase—							
4-wire	E	2IRt	$\frac{1000P}{2E \cos\phi}$	$\frac{0{\cdot}846Pl}{E^2e' \cos\phi}$	2IZt	$\frac{2IZt}{E}100$	$\frac{2EI \cos\phi}{1000}$
Single-phase—							
3-wire	2E	2IRt	$\frac{1000P}{2E \cos\phi}$	$\frac{0{\cdot}423Pl}{E^2e' \cos\phi}$	2IZt	$\frac{IZt}{E}100$	$\frac{2EI \cos\phi}{1000}$
2-wire	E	2IRt	$\frac{1000P}{E \cos\phi}$	$\frac{1{\cdot}690Pl}{E^2e' \cos\phi}$	2IZt	$\frac{2IZt}{E}100$	$\frac{EI \cos\phi}{1000}$

Temperature correction factor = t	1·00	1·09	1·13	1·14	1·16	1·18	1·20	1·24	1·36
Increase in temperature = ° F.	60	100	120	122	130	140	149	170	220

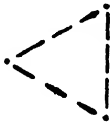
Where E = voltage between phase conductor and earth at receiving end.
R = resistance in ohms at 60° F. ; see increases in resistance due to increase in temperature, *t*.
A = sectional area, in square inch, per phase conductor in terms of volts drop taken as a percentage of E.
Z = impedance per phase conductor, in ohms.
P = power at receiving end in kW.
l = distance one way, in feet ; distance per mile = 5280 × *constant*, *i.e.* 5280 × 0·282 = 1489 for the three-phase 4-wire system.
cos ϕ = power factor of load.
e′ = percentage volts drop at receiving end, or volts drop as a percentage of E.
t = temperature correction factor, caused by the heat generated by the current, etc.

---

[1] More commonly called *two-phase* 5-wire system. It consists of two single-phase units with their centre points of windings, respectively, connected together, thus forming four *quarter* phases, or four two-phase relations.

yet the line reactance be the same, because the *effective* spacing for the two methods is the same.

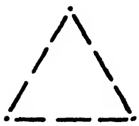
A



B

C

D



E

(B) This arrangement of conductors is essentially for double circuits; it is a very good arrangement, although (A) offers excellent advantages. For double-circuit lines it permits of shorter crossarms, of lesser spacing of line conductors, or of longer span-length. The phase conductors can be arranged so as to get the best advantages from the view-point of inductive reactance when using the double-delta disposition of the six phase-conductors. For this arrangement, the conductors at the same level may be of the same phase, hence a closer horizontal spacing; this also applies to (C).

(C) This arrangement permits of lesser spacing of line conductors than the following mentioned methods, but it requires a higher and a relatively heavier line support for the same size and number of line conductors. In areas subjected to ice-coating it is more dangerous than any other method, unless ample vertical conductor-separation is given. On the other hand, in a country not subjected to ice, it permits of a rather satisfactory double-circuit line, using copper conductors and extra high voltages.

(D) With this arrangement of line conductors the mean inductive reactance is the least for the least spacing (as with (A)), but the arrangement does not permit of the least possible spacing as with (A) due to two conductors being at one elevation. For a double-circuit line it may be equal to (A), and may have the advantage from wind of the four lower conductors being in line. However, (A) separation is based on the vertical distance, whereas (D) must always be based on the horizontal distance, which is about 14 per cent. greater.

(E) With this arrangement the mean inductive reactance is higher, and for higher voltage lines the mean charging current is greater, but the least mechanical stresses are obtained for the same size and number of conductors. Also, the total wind-load is less, the corona loss is less than with the equilateral conductor arrangement (see p. 100); and the conductor height above ground is the least, thus permitting better protection from lightning. In districts where prevailing winds are at high velocity and where single or double-circuit lines are to be used, this arrangement is good.

The separation of conductors must be considered in both the vertical and the horizontal planes. The *minimum vertical separation* of conductors, independent of the metal and size used, is given as follows:

$$s_v{}^* = x(S - S_t) + k \text{ (ins.)}.$$

Where S = *vertical* sag of conductor when loading with the specified (Regulation) or the maximum ice-coating in still air.

S_t = vertical sag of the conductor *without* ice-coating and in still air at the same temperature; S, S_t in inches.

E = voltage between these conductors.

$k = \frac{1}{2}$ in. per 1000 volts $= 0{\cdot}5E/1000$ ins.

x = constant ranging between 1·4 and 1·7.

The *minimum horizontal separation* of conductors, independent of the conductor metal and size used, is given as follows:

$$s_h = y + k \text{ (ins.)}.$$

Where y = maximum swing of conductor, in inches, for maximum horizontal wind pressure on bare conductor, with other conductor on same level loaded with maximum ice-coating at same temperature.

E = voltage between phase conductors.

$k = \frac{1}{2}$ in. per 1000 volts $= 0{\cdot}5E/1000$.

For long-span construction, very rarely required in distribution work, this formulæ would take the form:

$$s_h = k + z \text{ (ins.)}.$$

Where z = maximum pendulum swing of both conductors on same level, in inches.

The above methods for determining minimum separation of conductors, in the vertical and horizontal planes, would seem to be the more logical way of calculating these clearances.

For overhead clearance of conductors, 20 ft. is the minimum height specified by law at the present time. It is thought that no just reason can be given for this value of minimum height,

---

* Minimum of 12 inches for l.p. circuits.

which is made for 66,000 volts or 230 volts. The author proposes the following formulæ for *minimum overhead clearance* of conductors and wires:

$$H_c = C + k \text{ (ft.)}.$$

Where $k = \cdot0417$ ft. per 1000 volts $= (0\cdot5E/1000)/12$ (ft.).

C = minimum height, in feet, of conductors or wires taken at the highest temperature known with maximum current flow, for any particular span:

= spaces accessible to pedestrians *only* . = 15·0 ft.
open fields . . . . = 18·0 ,,
rural roads . . . . = 19·0 ,,
main roads (from rural to urban areas) . = 20·0 ,,
streets in towns . . . . . . = 21·0 ,,

E = voltage between phase conductors.

Thus, for a 6600-volt line we have a clearance for *open fields* of

$$18+\left(\frac{0\cdot5\times6600}{1000}\Big/12\right)=18\cdot275 \text{ ft.}$$

Or, for a 66,000-volt line in *open fields*, it is

$$18+\left(\frac{0\cdot5\times66{,}000}{1000}\Big/12\right)=20\cdot75 \text{ ft.}$$

And, for a 132,000-volt line in *open fields*, it is

$$18+\left(\frac{0\cdot5\times132{,}000}{1000}\Big/12\right)=23\cdot5 \text{ ft.}$$

In selecting a location for a transformer, other factors enter into the question independent of load centre. For several reasons a corner pole should never be chosen, and the pole chosen should be as free as possible from wiring (see fig. 31). A transformer pole should have initial strength to support the maximum load that might be installed—including the transformer, line equipment, as well as linemen doing repairs, etc. Transformers exceeding 10 kVA in capacity are difficult to handle, and should not be installed near the top of a pole; the maximum transformer capacity put on a single pole, of good construction, is 15 kVA.

In the case of pole-transformer erection for distribution lines, the transformers should be supported from the centre point of crossarms, and not hang out on the arms away from the pole, unless special supporting structures are used. And, where special conditions make it necessary to hang more than one transformer on a pole, if the requirements do not exceed, say, a 5 kW unit, then they should be hung on each side of (but near) the pole, not placed back to back. When special conditions require the installation of two transformers on a pole, each of a capacity greater than, say, 5 kW, they should not be supported from the crossarms on either side of the pole. All large transformers should be from separate crossarms at the pole—one above the other—preferably, a platform structure should be made for them to stand upon (see fig. 43). It is recommended not to erect more than one transformer on a pole, and the transformer should be supported by suitable irons, which pass over the top and grip the crossarm. This crossarm may be the topmost arm on the pole, or the lowermost primary crossarm on the pole. When very high poles are used, the transformer crossarm should be placed at a convenient height, not at the top of the pole. All transformer crossarms should be double arms. The number and arrangement of transformers at any point of the distribution system will depend on circumstances; good practice shows that:

> Individual transformers are used where consumers are too great a distance apart for the economical running of secondary mains; and
>
> Where the load is intermittent and where loads are heavy such that they interfere with the proper regulation of the voltage; but
>
> When the centre of distribution on the section of the secondary is changeable, due to the varying load conditions of the individual consumers' installations—although under such conditions the average maximum demand on the transformers will be comparatively constant—transformers may be desired for parallel operation. The transformers to be operated in parallel should preferably be about the same size, and be of the same type and form.
>
> The limit to the number of transformers to be operated in parallel can be determined by the relation of the load factor of the individual consumer to the total load factor of the transformers, having in mind the difference in the time of day of the maximum demand of the individual consumers connected to the transformers.
>
> In the parallel operation of distribution transformers they be located not too far apart because of the impedances of the circuit itself. The more common impedance-ratio of distribution transformers ranges between 3 and 5 per cent.—this impedance-ratio increases slightly with the transformer kVA capacity.

TABLE III.

TRANSFORMER CAPACITY IN kVA.

(Assuming $\cos\phi = 1{\cdot}0$.)

System.	Voltage of Phase-winding. (Primary.)	Voltage of Phase-winding. (Secondary.)	Capacity in kVA.
Single-phase—			
2-wire	E_p	E_s	$2E_sI_s/1000$
3-wire	E_p	E_s	$E_sI_s/1000$
Three-phase—			
Star, star	$E_p\sqrt{3}$	$E_s/\sqrt{3}$	$3E_sI_s/3000$
Delta, delta	E_p	E_s	$3E_sI_s/3000$
Star, delta	$E_p\sqrt{3}$	E_s	$3E_sI_s/3000$
V-V	E_p	E_s	$\sqrt{3}E_sI_s/1000\sqrt{3}$

Parallel Operation of Transformers.

Star-star will operate in parallel with delta-delta.
Delta-delta will operate in parallel with delta-delta.
Star-star will operate in parallel with star-star.
Star-delta will operate in parallel with star-delta.
Delta-star will operate in parallel with delta-star.
Delta-delta will operate in parallel with delta-delta.
Delta-star will operate in parallel with star-delta.
Star-delta will operate in parallel with delta-star.
V-V will operate in parallel with V-V.
T-T will operate in parallel with T-T.

TABLE IIIA.

MAXIMUM NORMAL INSULATION STRESSES IN TRANSFORMERS AND TO EARTH.

System Connection.	Maximum High-tension to Earth.	Maximum Low-tension to Earth.	Maximum High-tension to Low-tension.
Single-phase	0·500	0·500	0·550
Three-phase—			
Star-star	0·577	0·577	0·577
Delta-delta	0·577	0·577	0·608
Star-delta	0·577	0·577	0·630
V-V	0·577	1·150	0·645

TABLE IIIB.

MAXIMUM INSULATION STRESS WHEN ONE TERMINAL IS EARTHED.

System Connection.	Maximum High-tension to Earth.	Maximum Low-tension to Earth.	Maximum High-tension to Low-tension.
Single-phase . .	1·0	3·00	0·800
Three-phase—			
Star-star . .	1·0	3·21	0·764
Delta-delta . .	1·0	3·21	0·750
Star-delta . .	1·0	3·48	0·820
V-V . . .	1·0	4·26	0·866

TABLE IV.

INDUCTIVE REACTANCE PER 1000 YARDS OF HARD-DRAWN COPPER CONDUCTORS.

(For frequency of 50 cycles.)

Nominal Area in Sq. Inch.	Diameter of Conductor. Inches.	No. of Wires and Diameter in Inch.	X=Reactance in Ohms at 50 Cycles.										
			Separation of Conductors in Inches=*s*.										
			12	18	24	30	36	42	48	54	60	66	72
0·75	1·134	37/·162	·1912	·2145	·2309	·2439	·2543	·2632	·2709	·2776	·2837	·2891	·2940
0·60	1·008	37/·144	·1980	·2213	·2378	·2506	·2611	·2699	·2776	·2844	·2904	·2959	·3009
0·50	0·925	19/·185	·2029	·2262	·2427	·2556	·2660	·2749	·2826	·2893	·2954	·3008	·3058
0·40	0·830	19/·166	·2091	·2324	·2490	·2618	·2722	·2809	·2888	·2955	·3016	·3071	·3121
0·30	0·720	19/·144	·2173	·2406	·2571	·2699	·2804	·2893	·2969	·3037	·3098	·3152	·3202
0·25	0·645	7/·215	·2260	·2492	·2658	·2786	·2890	·2979	·3056	·3124	·3184	·3239	·3289
0·225	0·612	7/·204	·2290	·2523	·2688	·2816	·2921	·3009	·3086	·3154	·3214	·3269	·3319
0·200	0·579	7/·193	·2322	·2554	·2720	·2848	·2952	·3041	·3118	·3186	·3246	·3301	·3351
0·175	0·540	7/·180	·2362	·2595	·2760	·2888	·2992	·3081	·3158	·3226	·3286	·3341	·3391
0·150	0·498	7/·166	·2408	·2641	·2806	·2934	·3039	·3128	·3204	·3272	·3333	·3387	·3437
0·125	0·456	7/·152	·2459	·2693	·2857	·2985	·3090	·3178	·3255	·3323	·3383	·3438	·3488
0·100	0·408	7/·136	·2523	·2756	·2921	·3048	·3154	·3242	·3319	·3387	·3447	·3502	·3552
0·075	0·388	3/·180	·2584	·2817	·2982	·3110	·3215	·3303	·3380	·3448	·3508	·3563	·3613
0·050	0·317	3/·147	·2700	·2933	·3098	·3226	·3331	·3419	·3496	·3564	·3624	·3679	·3729
0·025	0·224	3/·104	·2899	·3132	·3297	·3426	·3530	·3619	·3696	·3763	·3824	·3878	·3928

Note.—See formulæ on p. 100.

For other *frequency* : Reactance=X1·2 for 60 cycles.
=X/2 for 25 cycles.

Also see page 257 for *voltage drop* in three-phase, 3-wire, 50-cycle overhead circuits.

CHAPTER III.

CALCULATIONS FOR DESIGN OF DISTRIBUTION LINES.

Overhead construction is an economic necessity, and universal practice is to carry distribution lines on wooden poles, quite satisfactory for safety and for continuity of service. What we look for is the highest ratio of safety to cost, and we obtain it best by this construction.

Distribution lines are restricted and limited in their *location* much more than transmission lines are; by locating them in alleys many advantages are obtained and objections to overhead lines are greatly minimised. *Joint occupancy* will facilitate line locations.

Loading conditions, as also minimum clearances and other factors in the design and construction of distribution lines, for this country, are still in a state of flux. They do not alter fundamental practices nor do they alter the basis for sag and tension results, which may be obtained directly from Table XXXVI. for ½-in. ice and 8·0 lb. wind; these values are correct to a high degree of refinement, and are applicable to all loading conditions and kind and type of conductor metal. That is to say, plot *b* and *c* values in terms of *a* for any value of *a* (for any loading and metal), the sag and tension is then read from the curves. For this country it is specified that lines shall be so designed and constructed that the stress in overhead copper conductors shall not exceed 26,880 lb./sq. in. (equivalent to 24 tons per square inch/factor of safety). And, the minimum permissible size for copper and aluminium must have an actual breaking strength of not less than 1237 lb., which, for copper, is equivalent to 0·0201 sq. in. and weighs 409 lb. per mile of length.

Single-phase 3-wire distribution will more generally be employed; this requires about the same amount of copper as the equivalent three-phase 4-wire feeders. The three-phase system is more suited to power distribution, and it requires much less copper in the feeder system than an equivalent single-phase 2-wire system. For the secondary distribution system the three-phase 4-wire and the single-phase 3-wire systems may be the two most important put into general use.

Copper and copper-alloy are the two most important conductors and, for distribution work in general, they should be used almost exclusively, especially in this country. Aluminium also has a field of use.

For the same voltage between conductors, same spacing and size of conductors, same power factor and frequency and line drop, a single-phase 2-wire system will transmit one-half the power in kW as that of a three-phase 3-wire system. By adding another conductor to the single-phase 2-wire system and supplying three-phase current the kW capacity of the line can be doubled for the same volts drop, etc.

WHEN designing lines for rural districts, all factors should be considered which lower the initial cost of the line as a whole and ensure minimum annual maintenance charges, including power losses, repairs, amortisation, interest on the capital outlay, and so forth. Materials that combine greatest economy in complete installation with the longest life in service will be most effective in reducing these maintenance and repair charges. The initial investment for poles and line ironwork (hardware) in short-span construction may be greater than the cost of conductors. Consequently, the longer spans with wooden structures will reduce the number of poles or frames and fittings, and should proportionally lower the total cost of the line.

Apart from copper, a desirable conductor [1] is now available that gives a high strength and high conductivity suitable for long distribution-line spans. This conductor has 77 *per cent. of the conductivity* of hard-drawn copper of equal size, and 30 per cent. greater strength. Compared with hard-drawn copper of equivalent conductance, it has 69 *per cent. greater strength.* It has the same density, modulus of elasticity and temperature coefficient of expansion as copper. It costs a little more for a given conductance than some other conductors, but the saving in construction costs through the use of longer spans, and the general increased reliability of the line coupled with its lower maintenance cost, makes its use a profitable investment. The use of a small diameter compared with other conductors of equal strength and conductance, reduces wind and sleet loads (see also p. 129 for comparison). This advantage, together with its high strength, moderate sag, and great resistance to the effects of arcs, lightning, insulator flash-over, abrasion, and corrosion will prolong the service under conditions where softer and less rugged conductors will fail. It is easy and inexpensive to erect, splice, joint, tap, and solder. Under normal operating conditions it shows no greater deterioration than all copper, and for this reason old lines can be taken down and restrung for new installations with perfect safety. By its use extensions to connect with new consumers can be made with the minimum of labour, material, and time. Tables giving physical properties and information on this class of copper-alloy conductor are on p. 116, also sag and tension tables for this conductor are given on pp. 179–183.

With this material, medium or short-span construction (which is common distribution practice) may offer a higher initial cost, but one often found to be cheaper and more satisfactory in the long run. Certain high-strength conductor manufacturers have greatly over-rated the advantages of long-span construction.

---

[1] Anaconda Copper Mining Co., New York, U.S.A.

For distribution work in general, copper and/or copper-alloy are the best and most reliable conductors; they are the most suitable and offer the best and most economically constructed lines from the operating engineer's standpoint. That is, they incorporate:

The lowest effective height, which keep down stresses from different causes;

The widest use of wooden supports, poles, crossarms, etc.;

The closest clearances of conductors, which improve voltage regulation, reduce bound charges, and lower the cost of supports, etc.;

Offer the highest insulation of the supports;

Permit of the best insulated line for the same insulators;

Generally permit of a line construction to give the best electrical performance.

Natural conditions and locality decide correct wind and ice-loadings, but rational methods for an assumed loading are either to:

Fix a loading for all lines, irrespective of voltage difference, and vary the factor of safety according to the particular design, and/or the construction, and/or the territory traversed by the line; or

Take a proportion of the resultant loading near to or at a temperature found best (say, 22° F.), and apply a reasonable factor of safety; or

Fix a loading for the smaller conductor sizes, without ice-coating, and follow the first mentioned.

At the present time the *factors of safety* for this country are:

Line conductors	2·0
Wood poles	3·5
Steel poles	2·5
Reinforced concrete poles	3·5
Foundations (up to April 1928)	2·5

Although not specified, we may also take:

Oak crossarms (vertical loads)	3·5
Steel crossarms	2·5
Stays (steel)	3·0
Stays (copperweld)	2·5

The conductor loading is based on 8·0 lb./sq. ft. **horizontal wind pressure ($13{\cdot}33 \times 0{\cdot}6 = 8{\cdot}0$) for all voltages, with $\frac{3}{8}$-in. radial ice for**

line voltages above 325 (a.c.), and $\frac{3}{16}$-in. radial ice for lower voltage lines, at a temperature of 22° F., respectively. True that a higher voltage is responsible for a higher line-support (affected by wind also by ice-coating), but it is hardly logical to refer to a mechanical loading in terms of voltage, especially a voltage of this value (325 V); it is more logical to modify loadings according to factor of safety and/or according to the district, *i.e.* dense, crowded (*ant.*), deserted, or thin. In New Zealand the specified loading is less for the former condition than for the latter; the idea would seem to account for greater exposure of the line and not for the greater number of people liable to danger. In most countries the opposite to this, or one loading, is the practice.

Per foot of length of conductor, or wire, the weight and wind pressure are as given below:

TABLE V.

ALLOWABLE WIND PRESSURE ON POWER-DISTRIBUTION LINES.

Part of Line.	Wind Pressure Allowance.
Line conductors .	8·0 lb. per sq. ft. on the *radial* ice-covered diameter (ice-covering $\frac{3}{8}''$ and $\frac{3}{16}''$ in thickness) at a temperature of 22° F.
Line supports .	13·0 lb. per sq. ft. of the projected area of solid and closed structures, and 1·5 times the projected area of latticed structures.

Weight of conductor only (bare, or covered with weatherproof braid, etc.) is

$$\mathrm{w.} \qquad (\mathrm{lb.}).$$

Weight of ice, based on ice being 57 lb. weight per cubic foot, is

$$\begin{aligned} \mathrm{w}' &= d'(d+d')(57 \times 0{\cdot}0218) \\ &= d'(d+d')(1{\cdot}2426) \qquad (\mathrm{lb.}). \end{aligned}$$

Weight of conductor, or wire, and ice is

$$w_{\prime\prime} = w + w' = w + d'(d+d')(1{\cdot}2426) \qquad (\mathrm{lb.}).$$

TABLE VI.

VALUES OF WIND VELOCITIES IN TERMS OF WIND PRESSURE FOR DIFFERENT CONSTANTS K.

Values of p (Lb./Sq. Ft.).	Values of Wind Velocities for					
	K=0·002.	0·0025.[1]	0·003.	0·0032.[2]	0·004.	0·005.
6·0	54·77	49·00	44·67	43·30	38·73	34·64
8·0[2]	63·25	56·57	51·63	50·00	44·72	40·00
11·0	74·16	66·33	60·55	58·63	52·44	46·89
13·0	80·62	72·11	65·82	63·74	56·95	50·99
15·0	86·61	74·46	70·71	68·55	61·24	54·77
18·0	94·87	84·85	77·47	75·00	67·09	60·00
20·0	100·00	89·44	81·62	79·06	70·71	63·25
22·0	100·50	93·80	85·63	82·92	74·16	66·33
Where V=	$\sqrt{500p}$	$\sqrt{400p}$	$\sqrt{333{\cdot}3p}$	$\sqrt{312{\cdot}5p}$	$\sqrt{250p}$	$\sqrt{200p}$

[1] In U.S.A. and Canada, general use is made of
$p=0{\cdot}0025V^2$ where $V=\sqrt{400p}$. $V=57$.

[2] Requirements of the British Regulations for Overhead Lines indicate that
$p=0{\cdot}0032V^2$ where $V=\sqrt{312{\cdot}5p}$. $V=50$.

Wind pressure on plane surface is $0{\cdot}00533V^2$, and actual effective wind area may be $0{\cdot}6\times$diameter. Then, for a wind velocity of 50 miles per hour, wind pressure on the projected area of conductors and smooth circular poles may be taken as

$$p=0{\cdot}00533\times 50^2\times 0{\cdot}6=8{\cdot}0 \text{ lb./sq. in.},$$

that is, for $p=kV^2$, $k=p/V^2=8/50^2=0{\cdot}0032$.

When V is known, the wind pressure can be found when the diameter (d) or (d_0) is given; thus

$$w_{,,,}=\frac{d_0V^2}{x}\text{ (lb.)},\qquad \begin{aligned} x&=3750 \text{ for } V=50,\\ &\doteq 4877 \;\;,,\;\; V=57, \end{aligned}$$

where d_0 is the total overall diameter of conductor or wire.

For the conductor only, where d and p are known, then

$$w_{,,,}=\frac{pd}{12}\text{ (lb.)},$$

and for conductor and ice, we have

$$w_{,,,}=\frac{p(d+2d')}{12}\ \text{(lb.)}.$$

Resultant load, is

$$\text{W}=\sqrt{(\text{vertical weight})^2+(\text{windage})^2}=\sqrt{w_{,,}^2+w_{,,,}^2}\ \text{(lb.)}.$$

Hence $w=w'/\cos\phi$; and $\tan\phi=w_{,,,}/\text{W}$.

Where w = weight of conductor or wire only, in pounds.
w' = weight of ice-coating only, in pounds.
$w_{,,,}$ = wind pressure in pounds.
$w_{,,}$ = weight of conductor and ice-load in pounds.
p = wind pressure in lb./sq. ft.
d = diameter of conductor in inches.
d' = radial thickness of ice in inches.
d_0 = overall diameter of conductor in inches.
V = wind velocity in miles per hour.
W = maximum or resultant load.

Relative wind and ice loadings on overhead lines depend on such principal factors as, *the* polyphase system and its required number of line conductors; the arrangement of conductors on the line; the kind of conductor metal and type of conductor; and the type of line support used. From the wind and ice standpoints the following practice can be quite generally accepted:

(1) Adoption of the *three-phase system* is best (see p. 18).

(2) *Copper conductor* is the best of all conductors (see pp. 111 and 132).

(3) *Solid conductor* is better than stranded from this viewpoint.

(4) *Horizontal arrangement* of conductors, as viewed from all aspects, is the best all-round disposition (see p. 156).

(5) *Wood poles* offer the best general advantages as they not only possess rounded outline to wind, but, due to their flexibility, to the short and moderate span construction, and to temperature changes, etc. they tend to throw off snow and ice loads (see p. 140).

Thus, a three-phase line with solid copper conductors horizontally strung on wood poles will, as a general rule, possess the best all-round advantages, as the wind loads and the accumulation of ice and snow are less, and what there is, is retained the least time. It is well to mention again that a *pole* should not be confused with a *frame*, such as the "A," which consists of two poles.

TABLE VII.

LOADS IN LB. PER LINEAL FOOT FOR BARE COPPER CONDUCTORS.

(Loading based on 8·0-lb. wind and ¼-in. thickness of ice.)

No. and Diameter (Inch) of Wires.	Nominal Area. (Square Inch.) (A).	Approx. Overall Diameter. (Inch.) (d).	Dead Load per Linear Foot. (Lb.) (w).	Vertical Load per Linear Foot. (Lb.) ($w_{,,}$).	Horizontal Load per Linear Foot. (Lb.) ($w_{,,,}$).	Maximum Load per Linear Foot. (Lb.) $W = \sqrt{w_{,,}^2 + w_{,,,}^2}$.	Angle of Resultant Load. $\frac{w_{,,}}{\sqrt{w_{,,}^2 + w_{,,,}^2}}$.	cos ϕ.
3/·104	0·025	0·224	0·1002	0·247	0·482	0·541	0·4566	62° 50′
3/·147	0·050	0·317	0·2002	0·376	0·544	0·661	0·5690	55° 18′
3/·180	0·075	0·388	0·3001	0·498	0·591	0·773	0·6442	49° 53′
7/·136	0·100	0·408	0·3986	0·603	0·605	0·854	0·7061	45° 5′
7/·152	0·125	0·456	0·4866	0·706	0·637	0·951	0·7430	42° 0′
7/·166	0·150	0·498	0·5940	0·826	0·665	1·060	0·7793	38° 48′
7/·180	0·175	0·540	0·6983	0·944	0·692	1·170	0·8069	36° 12′
7/·193	0·200	0·579	0·8026	1·060	0·719	1·281	0·8275	34° 10′
7/·204	0·225	0·612	0·8970	1·165	0·741	1·379	0·8448	32° 20′
7/·215	0·250	0·645	0·9963	1·274	0·763	1·484	0·8584	30° 50′
19/·144	0·300	0·720	1·2153	1·416	0·813	1·632	0·8676	29° 49′
19/·166	0·400	0·830	1·6150	1·950	0·886	2·141	0·9107	24° 23′
19/·185	0·500	0·925	2·0060	2·371	0·949	2·554	0·9283	21° 48′
37/·144	0·600	1·008	2·3676	2·758	1·000	2·933	0·9403	19° 52′
37/·162	0·750	1·134	2·9963	3·426	1·088	3·592	0·9538	17° 37′
Solid	0·01453	0·136	0·0560	0·176	0·424	0·448	0·3928	66° 52′
	0·01629	0·144	0·0627	0·185	0·429	0·467	0·3961	66° 40′
	0·01697	0·147	0·0642	0·187	0·431	0·470	0·3980	66° 33′
	0·01815	0·152	0·0700	0·195	0·434	0·476	0·4097	65° 49′
	0·02061	0·162	0·0795	0·205	0·441	0·486	0·4211	65° 5′
	0·02164	0·166	0·0834	0·213	0·444	0·492	0·4328	64° 21′
	0·02500	0·178	0·0959	0·229	0·452	0·506	0·4525	63° 6′
	0·02545	0·180	0·0981	0·231	0·453	0·508	0·4546	62° 57′
	0·02688	0·185	0·1040	0·239	0·456	0·514	0·4649	62° 18′
	0·02926	0·193	0·1130	0·251	0·462	0·525	0·4780	61° 27′
	0·03269	0·204	0·1260	0·267	0·469	0·539	0·4953	60° 18′
	0·03631	0·215	0·1400	0·284	0·476	0·554	0·5126	59° 10′
	0·05000	0·252	0·1930	0·349	0·501	0·610	0·5720	55° 6′
	0·07500	0·309	0·2890	0·463	0·539	0·710	0·6526	49° 15′
	0·10000	0·357	0·3860	0·574	0·571	0·809	0·7095	44° 48′
	0·12500	0·399	0·4820	0·683	0·599	0·908	0·7522	41° 13′
	0·15000	0·437	0·5780	0·792	0·624	1·007	0·7865	38° 8′
	0·17500	0·472	0·6750	0·899	0·647	1·107	0·8031	36° 34′

$w_{,,} = w + 0{\cdot}311(d + d')$ for ice = 1/4 in. thick = d'.
$w_{,,,} = 0{\cdot}666\ (0{\cdot}5 + d)$ for wind = 8·0 lb./sq. ft. = p.

For *American* (U.S.A.) values, see pp. 56, 113, 116, 117, 118, 119, 120, 121, 122, 123.

Table VIIa.

Loading Tables for Copper Conductors.*

(Based on $\frac{3}{16}$-in. ice loading and 8·0-lb. wind.)

No. and Diameter (Inch) of Wires.	Nominal Area. (Square Inch.) A.	Approx. Overall Diameter. (Inch.) d.	Dead Load per Lineal Foot. (Lb.) w.	(Vertical) [1] Load per Lineal Foot. (Lb.) $w_{\prime\prime}$.	(Horizontal) [2] Load per Lineal Foot. (Lb.) $w_{\prime\prime\prime}$.	Maximum Load per Lineal Foot. (Lb.) W.	Angle of Resultant Load. cos ϕ.	Values of Angle. sin ϕ.
3/·104	0·025	0·224	0·1002	0·1960	0·3989	0·4445	63° 50′	0·8975
3/·147	0·050	0·317	0·2002	0·3177	0·4609	0·5555	55° 7′	0·8203
3/·180	0·075	0·388	0·3001	0·4351	0·5086	0·6693	49° 27′	0·7598
7/·136	0·100	0·408	0·3986	0·5373	0·5220	0·7490	44° 4″	0·6967
✓7/·132	0·125	0·456	0·4866	0·6365	0·5540	0·8435	41° 1″	0·6562
7/·166	0·150	0·498	0·5940	0·7537	0·5820	0·9521	37° 40′	0·6110
7/·180	0·175	0·540	0·6983	0·8674	0·6100	1·0600	35° 5′	0·5750
7/·193	0·200	0·579	0·8026	0·9812	0·6360	1·1680	32° 51′	0·5424
7/·204	0·225	0·612	0·8970	1·0833	0·6580	1·2670	31° 14′	0·5185
7/·215	0·250	0·645	0·9963	1·1902	0·6800	1·3730	29° 55′	0·4987
19/·144	0·300	0·720	1·2153	1·4267	0·7300	1·6010	26° 59′	0·4537
19/·166	0·400	0·830	1·6150	1·8511	0·8033	2·0170	24° 11′	0·4096
19/·185	0·500	0·925	2·0060	2·2650	0·8666	2·4250	21° 0′	0·3583
37/·144	0·600	1·008	2·3676	2·6461	0·9220	2·8020	19° 12′	0·3288
37/·162	0·750	1·134	2·9963	3·3042	1·0060	3·4520	16° 50′	0·2896
Solid.	0·01453	0·136	0·0560	0·1314	0·3406	0·3652	69° 5′	0·9341
	0·01629	0·144	0·0627	0·1399	0·3460	0·3732	67° 59′	0·9270
	0·01697	0·147	0·0642	0·1421	0·3480	0·3758	67° 47′	0·9257
	0·01815	0·152	0·0700	0·1491	0·3513	0·3815	66° 0′	0·9200
	0·02061	0·162	0·0795	0·1609	0·3580	0·3924	65° 48′	0·9121
	0·02164	0·166	0·0834	0·1657	0·3606	0·3969	65° 20′	0·9087
	0·02500	0·178	0·0959	0·1811	0·3689	0·4100	63° 49′	0·8974
	0·02545	0·180	0·0981	0·1837	0·3700	0·4130	63° 35′	0·8956
	0·02688	0·185	0·1040	0·1908	0·3733	0·4191	62° 55′	0·8903
	0·02926	0·193	0·1130	0·2016	0·3786	0·4291	61° 59′	0·8828
	0·03269	0·204	0·1260	0·2172	0·3860	0·4493	61° 5′	0·7854
	0·03631	0·215	0·1400	0·2337	0·3933	0·4577	59° 18′	0·8599
	0·05000	0·252	0·1930	0·2954	0·4180	0·5118	54° 45′	0·8166
	0·07500	0·309	0·2890	0·4046	0·4560	0·6095	48° 25′	0·7480
	0·10000	0·359	0·3860	0·5133	0·4893	0·7092	43° 38′	0·6900
	0·12500	0·399	0·4820	0·6185	0·5160	0·8054	39° 50′	0·6405
	0·15000	0·437	0·5780	0·7235	0·5413	0·9036	36° 50′	0·5995
	0·17500	0·472	0·6750	0·8287	0·5647	1·0025	34° 15′	0·5628

Ice loading $= d' = \frac{3}{16}$ in. radial thickness.

[1] $w_{\prime\prime} = w + 0{\cdot}233(d + 0{\cdot}1875) = w + 1{\cdot}2426d'(d + d')$.

[2] $w_{\prime\prime\prime} = 0{\cdot}666(d + 0{\cdot}375) = \frac{2}{3}(d + 2d')$.

Angle in plane of resultant $= \frac{w_{\prime\prime}}{\mathrm{W}}$; $\phi = \tan \frac{w_{\prime\prime\prime}}{w_{\prime\prime}}$.

Sag and Tension Calculations.

The sag in direction of resultant at maximum loading and datum temperature is

$$S=\frac{Wl^2}{8T}\text{ (ft.)},$$

$$\text{horizontal component of sag}=S\times\sin\phi,$$
$$\text{vertical component of sag}\quad=S\times\cos\phi.$$

Length of conductor in span at datum temperature 0° F. with maximum loading is

$$L=l+\frac{8S^2}{3l}\text{ (ft.)}.$$

Elongation of conductor due to stress is

$$E=\frac{TL}{eA+L}\text{ (ft.)}.$$

Length of conductor at desired temperature above datum ° F. is

$$L_t'=a(t-t')L\text{ (ft.)}.$$

Length of unstressed conductor is

$$L_x=\frac{L}{1+\frac{T}{eA}}\text{ (ft.)}.$$

and the elastic shortening is

$$L_x'=L\frac{T'-T}{eA}\text{ (ft.)}.$$

Vertical sag at the desired temperature ° F. is

$$S_t=\sqrt{\frac{3l(L_t-l)}{8}}\text{ (ft.)},$$

and uniform tension corresponding to this sag is

$$T_t=\frac{wl^2}{8S_t}\text{ (lb.)}.$$

It should be noted that the algebraic sum of the elongation, E, and the length of conductor, L_t', at the desired temperature ° F., must be taken together and added to L to obtain L_t. The tension T′ at the higher temperature (without ice and wind loads) is different, and values of tension must be assumed so that the proper tension corresponds with that given by formulæ T_t.

TABLE VIII.

ANGLE OF DISPLACEMENT DUE TO WIND PRESSURE ON COPPER WIRE—STRANDED—BARE (HARD-DRAWN).[1]

(Loading based on 8·0 lb. wind and $\frac{1}{2}$-in. thickness of ice.)

No. and Diameter (Inch) of Wires.	Nominal Area. (Square Inch.)	Approx. Over-all Diameter. (Inch.)	Dead Load per Lineal Foot. (Lb.) (*a*)	(Vertical) Load per Lineal Foot. (Lb.) (*b*)	(Horizontal) Load per Lineal Foot. (Lb.) (*c*)	Maximum Load per Lineal Foot. Plane of Resultant. (Lb.) (*d*)	Angle of Resultant Load. (*e*)
3/·104	0·025	0·224	0·1002	0·549	0·816	0·984	56° 5′
3/·147	0·050	0·317	0·2002	0·707	0·878	1·127	51° 9′
3/·180	0·075	0·388	0·3001	0·851	0·926	1·257	47° 23′
7/·136	0·100	0·408	0·3986	0·962	0·939	1·342	44° 48′
7/·152	0·125	0·456	0·4866	1·079	0·971	1·451	42° 0′
7/·166	0·150	0·498	0·5940	1·213	0·999	1·571	39° 33′
7/·180	0·175	0·540	0·6983	1·343	1·027	1·690	37° 37′
7/·193	0·200	0·579	0·8026	1·472	1·053	1·810	35° 25′
7/·204	0·225	0·612	0·8970	1·587	1·074	1·915	34° 55′
7/·215	0·250	0·645	0·9963	1·706	1·089	2·019	32° 40′
19/·144	0·300	0·720	1·2153	1·972	1·146	2·280	30° 50′
19/·166	0·400	0·830	1·6150	2·440	1·220	2·730	26° 40′
19/·185	0·500	0·925	2·0060	2·990	1·284	3·200	23° 0′
37/·144	0·600	1·008	2·3676	3·303	1·338	3·563	21° 50′
37/·162	0·750	1·134	2·9963	4·009	1·423	4·177	19° 30′

[1] Angle of resultant load$=\cos\phi$, where ϕ=angle in plane of resultant$=b/d$. Also $\phi=\tan c/b$.

(See also p. 174 for sag and tension values based on the *catenary* equation; a useful chart can be prepared from the values *a*, *b*, and *c*, with *b* and *c* values as the sag and length curves, respectively, in terms of *a* values. For these curves, similar tabular values can be prepared for any loading, such as $\frac{3}{16}$ in., $\frac{1}{4}$ in., or $\frac{3}{8}$ in. ice, etc. and for any conductor metal.)

[TABLE VIIIA.

TABLE VIIIA.

ANGLE OF DISPLACEMENT DUE TO WIND PRESSURE ON COPPER WIRE—SOLID—BARE (HARD-DRAWN).

(Loading based on 8·0 lb. wind and ½-in. thickness of ice.)

Nominal Area. (Square Inch.)	Diameter. (Inch.)	Dead Load per Lineal Foot. (Lb.) (*a*)	(Vertical) Load per Lineal Foot. (Lb.) (*b*)	(Horizontal) Load per Lineal Foot. (Lb.) (*c*)	Maximum Load per Lineal Foot. Plane of Resultant. (Lb.) (*d*)	Angle of Resultant Load. (*e*)
0·01453	0·136	0·0560	0·451	0·758	0·882	59° 15′
0·01629	0·144	0·0627	0·462	0·763	0·892	58° 50′
0·01697	0·147	0·0642	0·466	0·765	0·896	58° 40′
0·01815	0·152	0·0700	0·474	0·768	0·902	58° 18′
0·02061	0·162	0·0795	0·490	0·775	0·917	57° 40′
0·02164	0·166	0·0834	0·497	0·778	0·923	57° 25′
0·02500	0·178	0·0959	0·516	0·786	0·940	56° 42′
0·02545	0·180	0·0981	0·520	0·787	0·943	56° 35′
0·02688	0·185	0·1040	0·528	0·790	0·951	56° 15′
0·02926	0·193	0·1130	0·542	0·795	0·962	55° 42′
0·03269	0·204	0·1260	0·563	0·803	0·981	54° 59′
0·03631	0·215	0·1400	0·583	0·810	0·998	51° 15′
0·05000	0·252	0·1930	0·659	0·835	1·064	51° 44′
0·07500	0·309	0·2890	0·791	0·873	1·178	47° 50′
0·10000	0·357	0·3860	0·917	0·905	1·288	44° 4′
0·12500	0·399	0·4820	1·040	0·933	1·379	41° 50′
0·15000	0·437	0·5780	1·159	0·959	1·504	39° 35′
0·17500	0·472	0·6750	1·277	0·982	1·610	37° 35′

Note.—*d* = resultant of *vertical loading* (*a*) and (*b*), and a *horizontal transverse load* (*c*), due to 8·0 lb. per sq. ft. wind pressure; (*a*) = dead weight of conductor; (*b*) = ½-in. radial coating of ice plus (*a*).

Where

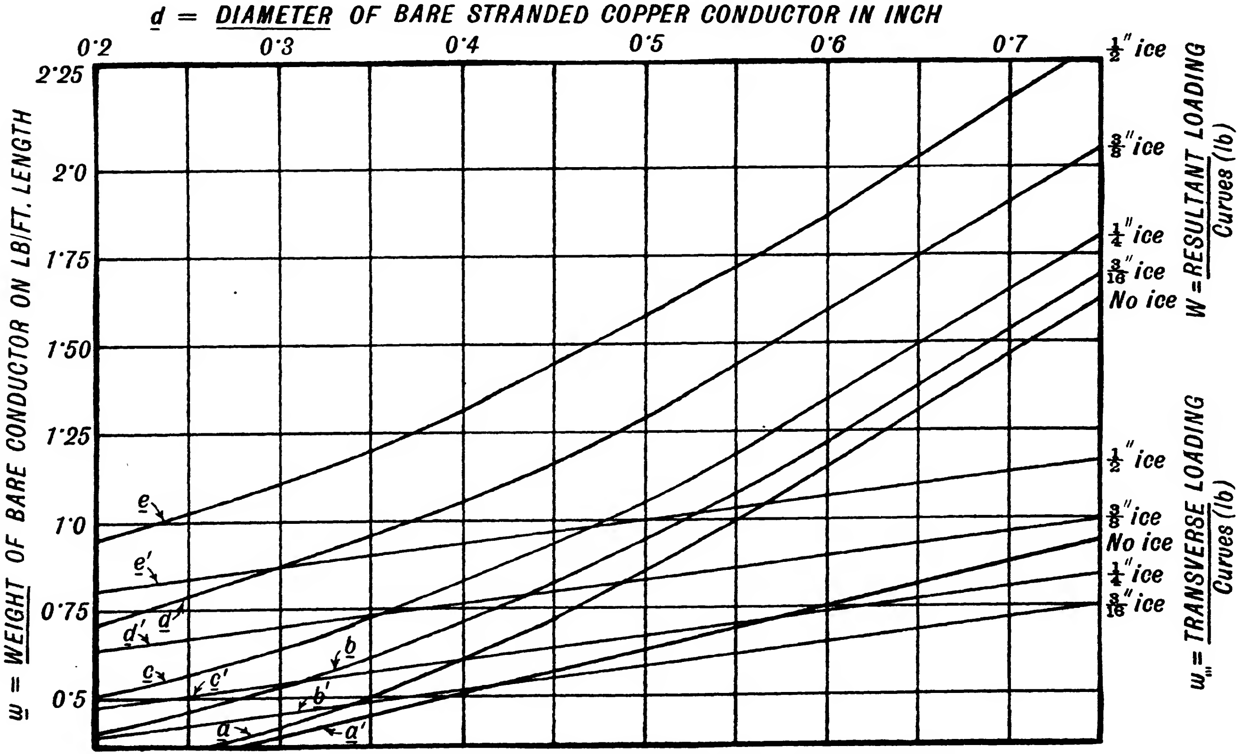
W = total resultant load in pounds per linear foot of conductor.
w = weight of conductor only, in pounds.
l = horizontal length of span, in feet.
A = area of conductor or wire, in square inches.
T_t = tension at temperature t', in pounds.
t' = increased temperature above datum, in ° F.
t = datum temperature, in ° F.

a = coefficient of expansion per ° F.
= 0·00000922 (British), 0·0000096 (America and Canada) for *Copper*.
= 0·0000126 (British), 0·0000128 (America and Canada) for *Aluminium*.
e = modulus of elasticity, in lb./sq. in.
= 18,000,000 (British), 16,000,000 (America and Canada) for *Copper*.
= 9,500,000 (British), 9,000,000 (America and Canada) for *Aluminium*.

(t in ° C.) Centigrade.		(t in ° F.) Fahrenheit.	(t in ° F.) Fahrenheit.		(t in ° C.) Centigrade.
0	=	32 Freezing Point.	22	=	− 5·56
5	=	41	32	=	0·00
10	=	50	40	=	4·44
15	=	59	50	=	10·00
20	=	68	60	=	15·55
25	=	77	70	=	21·11
30	=	86	80	=	26·66
35	=	95	90	=	32·22
40	=	104	100	=	37·77
45	=	113	110	=	43·33
50	=	122	120	=	48·88
55	=	131	130	=	54·44
60	=	140	140	=	60·00
65	=	149	150	=	65·55
70	=	158	160	=	71·10
75	=	167	170	=	76·66
80	=	176	180	=	82·21
85	=	185	190	=	87·77
90	=	194	200	=	93·32
95	=	203	210	=	98·88
100	=	212 Boiling Point.	212	=	100·00

To convert from one scale to another:

$$F.^\circ = \tfrac{9}{5}\,C.^\circ + 32$$
$$C.^\circ = \tfrac{5}{9}\,(F.^\circ - 32).$$



a = *Resultant* load with 25 lb horizontal wind *without* ice ; a′ = *Transverse* load.
b = ,, ,, ,, 8 ,, ,, ,, *with* $\frac{3}{16}$-in. ice : b′ = ,, ,,
c = ,, ,, ,, ,, ,, ,, ,, $\frac{1}{4}$,, : c′ = ,, ,,
d = ,, ,, ,, ,, ,, ,, ,, $\frac{3}{8}$,, : d′ = ,, ,,
e = ,, ,, ,, ,, ,, ,, ,, $\frac{1}{2}$,, : e′ = ,, ,,

FIG. 11.—Showing relative *resultant* and *horizontal transverse* loading conditions.

Calculation of Loads on Self-Supported Wood Poles.

In calculating the load on the pole it is only necessary to take account of the wind pressure, since the weight of the wires and conductors act vertically and do not increase the longitudinal loading. The horizontal transverse wind loading for different specified loading conditions is given in fig. 11 for different sizes of copper conductor; the resultant loadings are also given in the figure. Relative loadings and sizes of poles are also given on p. 81; these are of special interest in showing which of the different loading conditions are the easiest.

The conductors and wires are supposed to rest on the poles, but adjacent spans may be of different lengths, and consequently unbalanced, and two methods are available; that is, we may

> Take wind pressure on any one of the two adjacent full spans, for one conductor only if all conductors are of the same size and weight; or
>
> Take wind pressure on total number of conductors and wires, if of same size and weight, for the half of each of the two adjacent spans. This method is the best, and is the one on which the following formulæ are based.

We may also take, either

> The wind pressure on the plane surface and the average diameter of pole; or
>
> Wind pressure on the projected area of pole in terms of top and ground-line diameter of pole.

The wind pressure on a smooth circular pole is somewhat greater than for a wire or conductor, but as the value used in this country for the conductor is on the high side, it is acceptable for a smooth circular solid pole; that is

$$p = p' = 0{\cdot}0032V^2, \quad \text{where} \quad V = \sqrt{312{\cdot}5p'},$$

then, total wind pressure on conductors, when situated at one level above ground, is

$$\frac{pn(l'+l'')}{2} \text{ (lb.)}.$$

Bending moment due to wind on conductors at two different heights H′ H″ above ground is

$$M_w = \frac{pnH'(l'+l'')}{2} + \frac{pn'H''(l'+l'')}{2} \text{ (ft.-lb.)}.$$

Total wind pressure on pole is

$$\frac{p\mathrm{H}(d+2d_t)}{24}\ (\mathrm{lb.}).$$

In this country, the Electricity Commissioners now require top and ground diameter.

Bending moment at the ground due to wind on pole is

$$\mathrm{M}_p=\frac{p'\mathrm{H}^2(d+2d_t)}{72}\ (\mathrm{ft.\text{-}lb.})\ \text{(see example, p. 88).}$$

And the total bending moment on the self-supported wood pole (see Table Xa. *for red fir*) is

$$\mathrm{M}_c=\mathrm{M}_w+\mathrm{M}_p\ (\mathrm{ft.\text{-}lb.}).$$

Allowable resisting moment $=(\mathrm{M}_w+\mathrm{M}_p)\times$ factor of safety $=\mathrm{M}$; that is,

$$\mathrm{M}=0{\cdot}008179\,f\,d_g^3\qquad(\mathrm{ft.\ lb.})$$

$f=$ *Estimated* fibre stress of timber $=7800$-lb./sq. in. for red fir. And, diameter of pole at ground-line, is

$$d_g=\sqrt[3]{\frac{\mathrm{M}}{0{\cdot}008179f}}\qquad(\mathrm{inch}).$$

For ground-line diameter of each leg of "A" or "H" frame, take

$$0{\cdot}6d_g\ (\mathrm{in.})\qquad\text{(see p. 155).}$$

Where

d = diameter of pole above ground-line, in inches.
d_t = diameter of pole at top, in inches.
d_g = diameter of pole at ground-line, in inches.
p = wind pressure on wires, in pounds.
p' = wind pressure on pole, in pounds.
$l'l''$ = adjacent spans, in feet.
n = number of conductors or wires.
H = total height above ground-line, in feet.
H′H″ = height of conductors above ground-line, in feet.
F = factor of safety = 3·5 for this country *at present.*
$\pi=3{\cdot}1416$.

As an illustration of the effects of standards, the following shows the relative effect of different loadings on the size of wood pole required for the respective conditions given below, which are:

30 lb. wind pressure and a factor of safety of 10;
17 lb. wind pressure and a factor of safety of 8;
8 lb. wind pressure and ½-in. ice with factor of safety of 3·5;
8 lb. wind pressure and ½-in. ice with factor of safety of 3·5.

Example.—Three-phase 3-wire primary-feeder circuits are to be erected, and lines over different routes built with the poles 30 ft. above ground-level and for spans 150 ft. in length; the size of copper conductors decided on, and which are in the stores, are 0·10 sq. in., 0·05 sq. in., and 0·02 sq. in., respectively. It is required to find which specified loading condition offers the most economical size of pole. Calculations show the following:

Specified Loading.		Wind Pressure.	Size of Pole.	Conductor.
30 lb.	0 in. ice	207·0 lb.	$11\frac{3}{4}$ in.	0·05 sq. in. 0·252 in diameter.
17 ,,	0 in. ice	117·9 ,,	$8\frac{3}{4}$,,	
8 ,,	$\frac{1}{4}$ in. ice	225·6 ,,	$7\frac{1}{2}$,,	
8 ,,	$\frac{1}{2}$ in. ice	375·6 ,,	9·0 ,,	
30 ,,	0 in. ice	279·0 ,,	$12\frac{3}{4}$,,	0·10 sq. in. 0·372 in. diameter.
17 ,,	0 in. ice	158·1 ,,	$9\frac{1}{2}$,,	
8 ,,	$\frac{1}{4}$ in. ice	261·6 ,,	$8\frac{3}{4}$,,	
8 ,,	$\frac{1}{2}$ in. ice	411·6 ,,	$9\frac{1}{4}$,,	
30 ,,	0 in. ice	120·9 ,,	$11\frac{1}{4}$,,	0·02 sq. in. 0·16 in. diameter.
17 ,,	0 in. ice	68·1 ,,	8 ,,	
8 ,,	$\frac{1}{4}$ in. ice	198·0 ,,	7 ,,	
8 ,,	$\frac{1}{2}$ in. ice	348·9 ,,	$8\frac{3}{4}$,,	

Note.—For " A " frame (for each leg) multiply the above values for size of pole by 0·6.

For *struts*, the average diameter of a round strut is

$$d_m = \sqrt[4]{\left(\frac{\text{TH}^2 \times \text{factor of safety required}}{5000}\right)} \text{ (in.)}.$$

Where H = height of strut in feet.
T = load on strut in pounds.

Approximate *deflection* of single round fir poles at point of pull is given by

$$D = \frac{11{,}700 W' H^3}{e d_g^4} \text{ (in.)}.$$

Where: H = height of pull from ground-line, in feet.
W' = resultant pull at right angles to pole, in pounds.
d_g = diameter of pole at ground-line, in inches.
e = modulus of elasticity
= 1,400,000 lb./sq. in.

INSULATOR-PIN STRENGTH CALCULATIONS.

The theoretical strength of a pin and arm are usually computed from the standard beam and column formulæ, but actual practice does not always compare favourably with the figures obtained from these formulæ.

For wrought-iron solid pins, the bending moment is given by

$$M' = W'l \text{ (lb.)},$$

and fibre stress for a round solid pin is

$$f = \frac{M'}{k},$$

where

k = section modulus = $0{\cdot}0981d^3$;
d = diameter of pin, in inch.
l = length of pin from crossarm to application of load, in inches.
W' = unbalanced pull applied at top of pin, in pounds.
Allowable fibre stress of wrought iron = 45,000 lb./sq. in.
Elastic limit is 50 per cent. of breaking stress.

CROSSARM STRENGTH CALCULATIONS FOR VERTICAL WEIGHT.

For a single crossarm the bending moment due to vertical weight is

$$M_c = (x_1l' + x''l'' + x'''l''' + \ . \ . \ . \ + x^nl^n) \text{ (in.-lb.)}$$

$l'l''l'''$ = distance from the centre of pole to centre of pins, in inches.
$x'x''x'''$ = total weight of respective conductors supported by the pins, in pounds.

If there are, for instance, three conductors and they are of the same weight, the weights are added together making w, then

$$x' = w\left(\frac{l' + l''}{2}\right),$$

where l' and l'' are the lengths of adjacent spans, in feet.

The fibre stress in the crossarm (*wooden*) of the ordinary *rectangular* form is

$$f_c = M_c\left(\frac{6}{yz^2}\right),$$

where z = depth, or vertical thickness of crossarm, in inches.
y = width, or horizontal thickness of crossarm, in inches.

The point of maximum bending moment is at the bolt hole where the crossarm is attached to the pole. Allowing for this, the fibre stress without braces becomes

$$f_c = M_c\left(\frac{6z}{y(z^3-d_c^3)}\right),$$

where d_c =diameter of bolt hole, in inch.

For square crossarm of wood, the section modulus $=z^3/6$.

For a channel-iron crossarm, the section modulus $=Az'/3{\cdot}67$,

where A =total area of section; z' =channel width.

With *braces*, where f_h is equal to horizontal stress,

$$f_c' = f_c + [f_h/y(z-d_c)].$$

TABLE IX.

PROPERTIES OF OAK CROSSARMS

(in *inch* units).

Size in Inches.		Section Modulus.		Moments of Inertia.		Radii of Gyration.	
y.	z.	y'.	z'.	y'.	z'.	y'.	z'.
4	4	10·65	10·65	21·3	21·3	1·153	1·153
4	3	8·0	6·0	16·0	9·0	1·153	0·866
3	3	4·5	4·5	6·75	6·75	0·866	0·866

z = depth, or vertical thickness of crossarm, in inches.
y = width, or horizontal ,, ,, ,,
y' = horizontal axis of crossarm.
z' = vertical ,, ,,
k = section modulus, for rectangular section $=y\,z^2/6$.
,, ,, ,, round section is $0{\cdot}0981d^3$, where d = diameter.
,, ,, ,, hollow-round section is $0{\cdot}0981(d^4-D^4)/d$, where D = inside diameter.

TABLE X.

STRENGTH OF TIMBER FOR POLES.

Materials.	Ultimate Fibre Stress in Lb. per Sq. In.	
	(Bending.)	(Compression.)
White oak	8000	$8000\,(1-(L/60d))$
Red fir	7800	$7800\,(1-(L/60d))$
Yellow pine . . .	6000	$6000\,(1-(L/60d))$
Red cedar	4500	$4500\,(1-(L/60d))$

TABLE XA.

MAXIMUM ALLOWABLE RESISTING (BENDING) MOMENT FOR RED FIR.
(*Formulæ :* $M = d^3 \times 63{\cdot}8$.)

Diameter of Pole in Inches. (d).	Moment in Ft.-Lb. (M).	Diameter of Pole in Inches. (d).	Moment in Ft.-Lb. (M).
6·0	13,800	11·00	84,800
6·25	15,600	11·25	90,800
6·50	17,500	11·50	97,000
6·75	19,600	11·75	103,400
7·00	21,900	12·00	110,600
7·25	24,300	12·25	117,200
7·50	26,900	12·50	124,500
7·75	29,700	12·75	132,200
8·00	32,600	13·00	140,100
8·25	35,800	13·25	148,300
8·50	39,100	13·50	156,800
8·75	42,700	13·75	165,800
9·00	46,500	14·00	175,000
9·25	50,400	15·00	215,100
9·50	54,700	16·00	261,200
9·75	59,030	17·00	313,300
10·00	63,800	18·00	372,000
10·25	68,700	19·00	437,600
10·50	73,900	20·00	510,000
10·75	79,200	21·00	591,000

It is of interest to note that:

(*a*) By doubling the diameter, d, the moment, M, is increased *eight* times.

(*b*) By doubling the factor of safety, F, the diameter, d, is increased 1·26 *times*, *i.e.* roughly 25 per cent. greater diameter for twice the increase in the factor of safety.

(*c*) By doubling the bending moment, M, the diameter is increased 1·26 *times*.

Thus, doubling the factor of safety or/and bending moment increases the diameter of pole a little over 25 per cent.

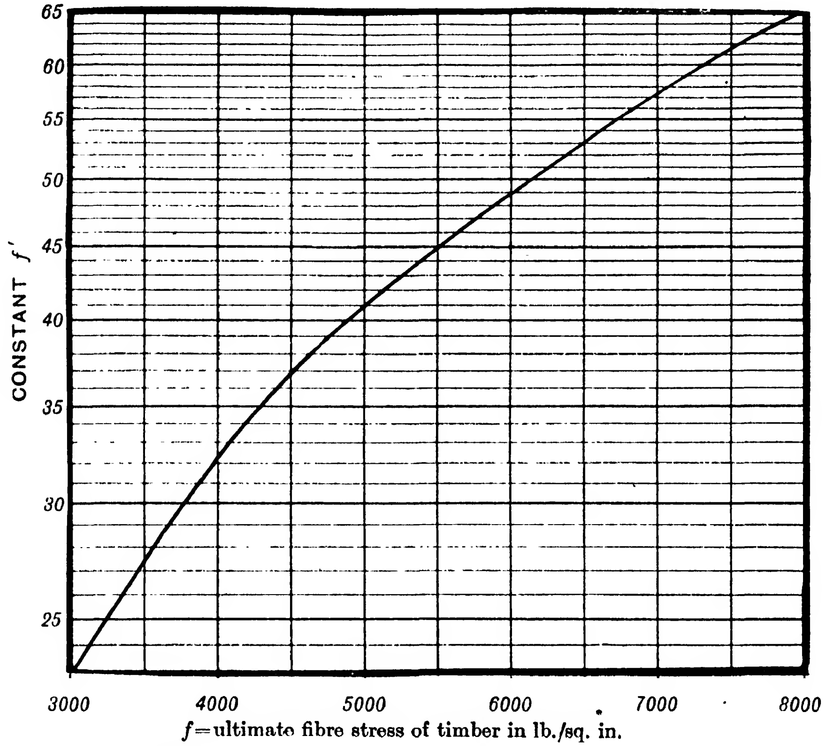
Example.—Let ground-line diameter of creosoted red-fir pole be 14 in., what is its maximum allowable bending moment ?

$$M = d^3 \times 63{\cdot}8 = (14)^3 \times 63{\cdot}8 = 2744 \times 63{\cdot}8 = 175{,}067 \text{ ft.-lb.}$$

When the moment and factor of safety are known (usually given by calculations), the size of pole is found from:

$$d = \sqrt[3]{(M/f')}\ (\text{in.}),$$

where M = allowable resisting moment in ft.-lb.; f' = fibre stress factor.



Formulæ :—

Maximum bending moment $= d^3f' - M$ (see p. 86),

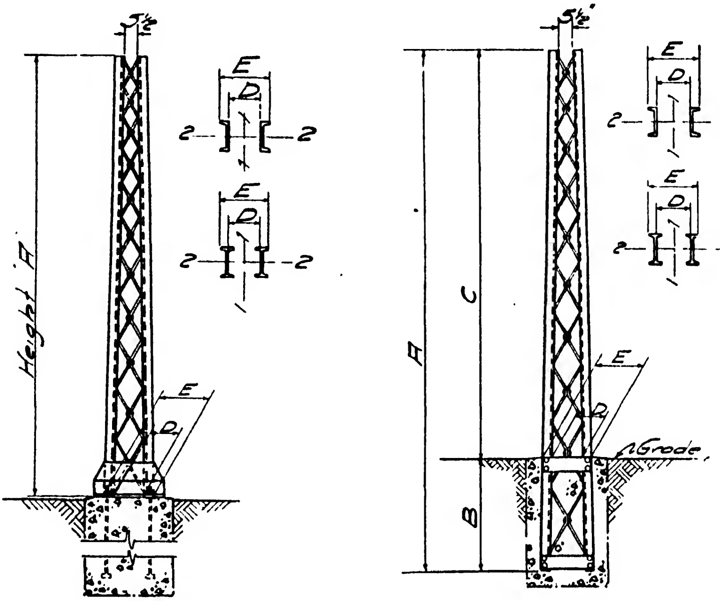
and *Diameter of wood pole* $\sqrt[3]{M/f'} = d$ (see p. 85).

FIG. 12.—Practical values for any class of timber used for poles coming within the ultimate fibre stresses of 3000 and 8000 lb. per sq. in.

Example.—It is calculated that the allowable bending moment on a creosoted red-fir pole is 175,000 ft.-lb. at the ground-line of a pole set 30 ft. in height above ground; find its diameter at ground-line.

$$d = \sqrt[3]{(175{,}000/63{\cdot}8)} = \sqrt[3]{2744} = 14{\cdot}0 \text{ ins.}$$

Fig. 12 can be used for all classes of timber where the ultimate fibre stress is between 3000 and 8000 lb./sq. in. The name of a given timber is purely a matter for classification; if its ultimate fibre stress is within 3000 and 8000, then the maximum bending moment can be found from fig. 12. According to the timber classifications and the assumed *allowable* fibre stresses of timbers, we have:



Anchor Bolt Base **Embedded Base**

FIG. 13.—"*Truscon*" copper-alloy steel poles.

$$M = d^3 f' = \text{maximum allowable resisting moment}$$

where d = diameter of round pole in inches.
$f' = 65{\cdot}45$ for $f = 8000$ lb./sq. in. (white oak)
$= 63{\cdot}8$ „ $f = 7800$ „ (red fir)
$= 49{\cdot}1$ „ $f = 6000$ „ (yellow pine)
$= 36{\cdot}8$ „ $f = 4500$ „ (red cedar)
f = ultimate fibre stress of timber
f/F = allowable fibre stress of timber
F = factor of safety $= 3{\cdot}5$ for this country.

Showing the use of Table XA. let us take the following example:—

Example.—A 6600-volt primary three-phase 4-wire feeder is to be run from a transforming centre to a new load; the route is level and straight, across fields in rural territory. The spans

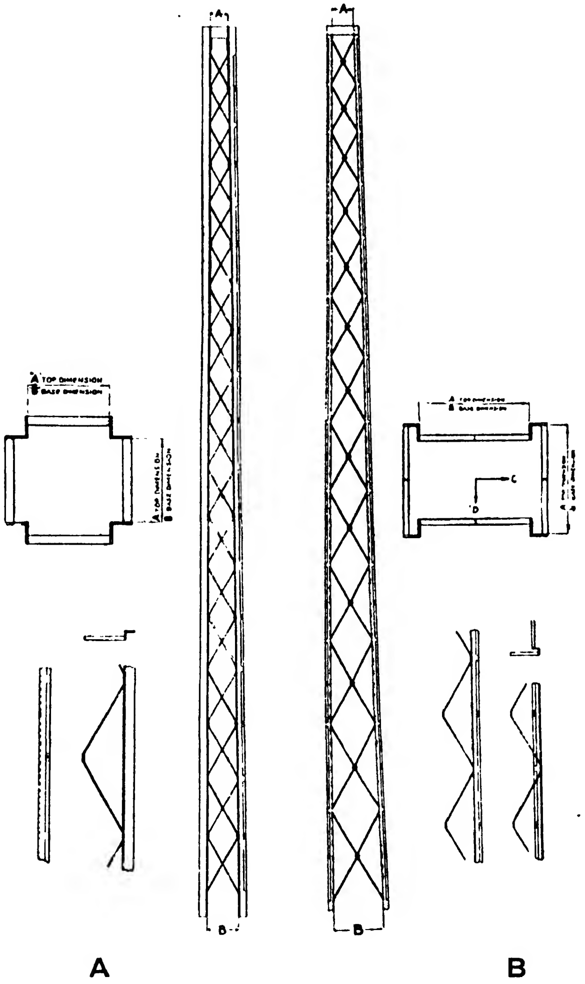


FIG. 13A.—Steel lattice poles (Walter Bates). (B) is the cross lattice—combination internal and external lacing. (A) is the single lattice—external lacing.

average 250 ft. each. The conductor disposition is flat, with the four wires on one oak crossarm. The size of conductors is 0·05 sq. in. (3/·147) h.d. bare copper, including the neutral; the loading is $\frac{3}{8}$-in. ice and 8·0-lb. wind (*just allowed* at the present time in this country for 6600 volts); see fig. 11, page 78, for $\frac{3}{8}$-in. ice loading. It is required to find the size of pole.

Calculation.—Overall height of pole is:

Height for minimum *permissible* ground clearance (this is high, and therefore allows for 1·0 ft. spare at top for arm)	20·0 ft.
Sag of 3/·147 copper conductor at 100° F. temperature rise for span of 250 ft.	3·0 ,,
Depth set in ground	5·5 ,,
	28·5 ,,

Overall height above ground-line, allowing for an extra for uneven ground between spans, etc. of 1·0 ft. is

$$1+28{\cdot}5-5{\cdot}5=24{\cdot}0 \text{ ft.}$$

The Electricity Commissioners now require to know the top diameter, and diameter 5·0 ft. from the butt of pole; therefore, let us take a standard "stout" creosoted red-fir pole of 10·5 in. diameter, 5·0 ft. from the butt, with 8·5 in. diameter at top (see Table XXXIII.); then, bending moment due to wind on conductors, is

$$4\times0{\cdot}710\times24\times250=17{,}040 \text{ ft.-lb.}$$

Bending moment at the ground due to wind on pole is

$$\frac{8\times(24)^2\times(10{\cdot}5+2\times8{\cdot}5)}{72}=1760 \text{ ft.-lb.}$$

Total bending moment on self-supporting pole is

$$=17{,}040+1760=18{,}800 \text{ ft.-lb.}$$

The maximum allowable moment is

$$18{,}800\times\text{factor of safety}=18{,}800\times3{\cdot}5=65{,}800 \text{ ft.-lb.}$$

From Table Xa. size of pole is seen to be 10 in. at ground-line, or 5·5 ft. from the butt.

It is also calculated from

$$d=\sqrt[3]{M/f'}=\sqrt[3]{65{,}800/63{\cdot}8}=10 \text{ in.}$$

However, a 10·5 in. diameter pole, taken at a point 5·0 ft. from the butt, is decided on.

TABLE XI.

PROPERTIES OF TRUSCON POLES WITH ANCHOR BOLT BASES.

	See Fig. 13.			Axis 1–1 Transverse. See Fig. 13.			Axis 2–2 Longitudinal. See Fig. 13.		
Size.	Height A.	D.	E.	Moment of Inertia.	Section Modulus.	Safe Load 2′ 0″ from Top at 20,000 Lb. per Sq. In.	Moment of Inertia.	Section Modulus.	Safe Load 2′ 0″ from Top at 20,000 Lb. per Sq. In.
Two 5-inch channels at 6·7 lb. per ft.	20 0	10·50	14·0	110·7	15·8	1460	14·6	5·8	540
	25 0	11·75	15·25	135·5	17·7	1285	14·6	5·8	420
	30 0	13·00	16·5	163·0	19·7	1170	14·6	5·8	345
Two 6-inch channels at 8·2 lb. per ft.	20 0	10·50	14·3	137·4	19·1	1770	25·7	8·6	795
	25–0	11·75	15·6	168·0	21·5	1560	25·7	8·6	625
	30–0	13·00	16·8	202·1	24·0	1430	25·7	8·6	510
	35–0	14·25	18·1	239·1	26·4	1330	25·7	8·6	435
Two 7-inch channels at 9·8 lb. per ft.	25–0	11·75	15·9	207·6	26·0	1885	41·9	12·0	870
	30 0	13·00	17·2	249·1	29·0	1725	41·9	12·0	710
	35–0	14·25	18·4	294·0	31·9	1610	41·9	12·0	605
	40 0	15·50	19·7	343·0	34·9	1530	41·9	12·0	525
Two 8-inch channels at 11·5 lb. per ft.	25–0	11·75	16·3	243·7	29·9	2170	64·0	16·0	1160
	30–0	13·00	17·5	292·3	33·4	1985	64·0	16·0	950
	35–0	14·25	18·8	345·0	36·8	1860	64·0	16·0	810
	40–0	15·50	20·0	401·1	40·1	1760	64·0	16·0	700
	45–0	16·75	21·3	463·4	43·5	1685	64·0	16·0	620
Two 9-inch channels at 13·4 lb. per ft.	25–0	11·75	16·6	289·3	34·8	2525	94·0	20·9	1515
	30–0	13·00	17·9	347·2	38·9	2320	94·0	20·9	1245
	35–0	14·25	19·1	409·1	42·9	2165	94·0	20·9	1055
	40–0	15·50	20·4	477·4	46·9	2060	94·0	20·9	915
	45–0	16·75	21·6	549·7	50·8	1970	94·0	20·9	810
Two 10-inch channels at 15·3 lb. per ft.	30–0	13·00	18·2	407·5	44·8	2670	133·2	26·6	1585
	35–0	14·25	19·5	481·6	49·5	2500	133·2	26·6	1345
	40–0	15·50	20·7	559·8	54·0	2370	133·2	26·6	1170
	45–0	16·75	22·0	645·1	58·7	2275	133·2	26·6	1035
	50–0	18·00	23·2	734·8	63·3	2200	133·2	26·6	925
Two 12-inch channels at 20·7 lb. per ft.	30–0	13·00	18·9	574·5	60·8	3615	255·5	42·6	2535
	35–0	14·25	20·1	674·1	67·1	3390	255·5	42·6	2150
	40–0	15·50	21·4	781·6	73·2	3210	255·5	42·6	1870
	45–0	16·75	22·6	900·1	79·5	3080	255·5	42·6	1650
	50–0	18·00	23·9	1025·8	85·8	2975	255·5	42·6	1480

TABLE XIA.

PROPERTIES OF TRUSCON POLES EMBEDDED IN CONCRETE.

Size.	See Fig. 13.					Axis 1-1 Transverse. See Fig. 13.			Axis 2-2 Longitudinal. See Fig. 13.		
	A.	B.	C.	D.	E.	Moment of Inertia.	Section Modulus.	Safe Load 2′ 0″ from Top at 20,000 lb. per Sq. In.	Moment of Inertia.	Section Modulus.	Safe Load 2′ 0″ from Top at 20,000 lb. per Sq. In.
Two 5-in. channels at 6·7 lb. per ft.	20–0	4–0	16–0	9·5	13·0	92·5	14·2	1690	14·6	5·8	695
	25–0	5–0	20–0	10·5	14·0	110·5	15·8	1460	14·6	5·8	540
	30–0	5–6	24–6	11·6	15·1	131·9	17·5	1295	14·6	5·8	430
	35–0	6–0	29–0	12·7	16·2	155·8	19·2	1185	14·6	5·8	360
Two 6-in. channels at 8·2 lb. per ft.	20–0	4–0	16–0	9·5	13·3	115·7	17·4	2070	25·7	8·6	1020
	25–0	5–0	20–0	10·5	14·3	138·0	19·1	1770	25·7	8·6	795
	30–0	5–6	24–6	11·6	15·5	164·5	21·2	1570	25·7	8·6	635
	35–0	6–0	29–0	12·7	16·6	193·8	23·4	1405	25·7	8·6	530
	40–0	6–0	34–0	14·0	17·8	231·4	26·0	1355	25·7	8·6	445
Two 7-in. channels at 9·8 lb. per ft.	25–0	5–0	20–0	10·5	14·7	169·6	23·1	2140	41·9	12·0	1110
	30–0	5–6	24–6	11·6	15·8	202·5	25·6	1900	41·9	12·0	890
	35–0	6–0	29–0	12·7	16·9	238·1	28·3	1745	41·9	12·0	740
	40–0	6–0	34–0	14·0	18·2	284·7	31·3	1630	41·9	12·0	625
	45–0	6–6	38–6	15·1	19·3	325·5	33·7	1540	41·9	12·0	560
Two 8-in. channels at 11·5 lb. per ft.	25–0	5–0	20–0	10·5	15·0	199·4	26·6	2460	61·0	16·0	1485
	30–0	5–6	24–6	11·6	16·1	238·6	29·6	2190	64·0	16·0	1190
	35–0	6–0	29–0	12·7	17·3	279·4	32·4	1995	64·0	16·0	990
	40–0	6–0	34–0	14·0	18·5	333·0	36·0	1875	64·0	16·0	835
	45–0	6–6	38–6	15·1	19·6	382·2	39·0	1780	64·0	16·0	730
	50–0	6–6	43–6	16·4	20·9	446·0	42·4	1705	64·0	16·0	645
Two 9-in. channels at 13·4 lb. per ft.	30–0	5–6	24–6	11·6	16·5	283·0	34·4	2550	94·0	20·9	1550
	35–0	6–0	29–0	12·7	17·6	332·5	37·9	2340	91·0	20·9	1290
	40–0	6–0	34–0	14·0	18·9	349·0	42·0	2190	94·0	20·9	1090
	45–0	6–6	38–6	15·1	20·0	454·0	45·5	2075	94·0	20·9	955
	50–0	6–6	43–6	16·4	21·3	528·0	49·6	1990	94·0	20·9	840
Two 10-in. channels at 15·3 lb. per ft.	30–0	5–6	24–6	11·6	16·8	333·0	39·7	2940	133·2	26·6	1975
	35–0	6–0	29–0	12·7	17·9	390·2	42·6	2700	133·2	26·6	1645
	40–0	6–0	34–0	14·0	19·2	465·6	48·5	2530	133·2	26·6	1385
	45–0	6–6	38–6	15·1	20·3	533·7	52·5	2400	133·2	26·6	1215
	50–0	6–6	43–6	16·4	21·6	619·2	57·4	2305	133·2	26·6	1070
Two 12-in. channels at 20·7 lb. per ft.	35–0	6–0	29–0	12·7	18·6	551·4	59·3	3660	255·5	42·6	2630
	40–0	6–0	34–0	14·0	19·9	649·8	65·5	3415	255·5	42·6	2220
	45–0	6–6	38–6	15·1	21·0	745·8	70·5	3220	255·5	42·6	1945
	50–0	6–6	43–6	16·4	22·3	865·8	77·7	3120	255·5	42·6	1710
Two 8-in. I-beams at 17·5 lb. per ft.	40–0	6–0	34–0	14·0	19·2	475·5	49·5	2580	116·2	29·1	1515
	45–0	6–6	38–6	15·1	20·3	549·9	54·2	2480	116·2	29·1	1325
	50–0	6–6	43–6	16·4	21·6	644·9	59·7	2400	116·2	29·1	1165
Two 10-in. I-beams at 22·4 lb. per ft.	40–0	6–0	34–0	14·0	19·7	618·2	62·5	3280	226·6	45·3	2360
	45–0	6–6	38–6	15·1	20·9	714·5	68·4	3125	226·6	45·3	2070
	50–0	6–6	43–6	16·4	22·1	837·4	75·6	3030	226·6	45·3	1820
Two 12-in. I-beams at 27·9 lb. per ft.	40–0	6–0	34–0	14·0	20·3	784·2	77·2	4020	398·1	66·4	3455
	45–0	6–6	38–6	15·1	21·4	902·0	84·5	3865	398·1	66·4	3030
	50–0	6–6	43–6	16·4	22·7	1056·7	93·2	3750	398·1	66·4	2665

Reinforced-concrete poles are much used on the European Continent; the author's experience is that they are too heavy, expensive, and liable to permanent bending. The tubular steel pole is the least desirable pole; it has been much used in countries troubled with white ants and the like, also for trolley (tramway) poles. The class of steel pole shown in fig. 13 and fig. 13A is far superior.

TABLE XIB.

(BATES.)

CROSS LATTICE–COMBINATION INTERNAL AND EXTERNAL LACING STEEL POLES.

Height in Feet.	Dimensions.		Weight in Pounds.	Pole set on Pier.		Pole set in Concrete.		
	"A."	"B."		Direction "C."	Direction "D."	Depth in Feet.	Direction "C."	Direction "D."
	(Fig. 13A).			Calculated.			Calculated.	
				Failure Load.	Failure Load.		Failure Load.	Failure Load.
3 × 3 × ¼-inch L Poles.								
40		29	846	3,460	3,260	6½	3,840	3,600
45		31	947	3,280	3,100	6½	3,560	3,350
50	13	33	1,071	3,040	2,970	7·0	3,350	3,160
55		35	1,172	2,780	2,650	7·0	3,180	3,000
60		37	1,272	2,500	2,380	7½	2,860	2,700
3½ × 3½ × 5/16-inch L Poles.								
40		30¾	1,234	5,530	5,160	6½	6,100	5,660
45		32¾	1,380	5,170	4,850	6½	5,650	5,260
50	14¾	34¾	1,565	4,920	4,640	7	5,300	4,960
55		36¾	1,712	4,600	4,430	7	5,000	4,700
60		38¾	1,858	4,350	4,120	7½	4,700	4,430
4 × 4 × ⅜-inch L Poles.								
40		32½	1,666	8,300	7,650	6½	9,160	8,440
45		34½	1,864	7,680	7,160	6½	8,400	7,780
50	16½	36½	2,111	7,250	6,800	7	7,800	7,250
55		38½	2,310	7,060	6,600	7	7,360	6,880
60		40½	2,509	6,630	6,240	7½	7,060	6,630
5 × 5 × ⅜-inch L Poles.								
40		34½	2,088	11,950	10,800	6½	13,300	12,000
45		36½	2,336	10,800	9,900	6½	12,100	11,000
50	18½	38½	2,655	10,400	9,550	7	11,300	10,300
55		40½	2,903	9,900	9,120	7	10,700	9,810
60		42½	3,151	9,550	8,820	7½	10,200	9,380

[TABLE XIB.—*continued.*

TABLE XIB.—(*continued*).

Height in Feet.	Dimensions.		Weight in Pounds.	Pole set on Pier.		Pole set in Concrete.		
	"A."	"B."		Direction "C."	Direction "D."	Depth in Feet.	Direction "C."	Direction "D."
	(Fig. 13A).			Calculated.			Calculated.	
				Failure Load.	Failure Load.		Failure Load.	Failure Load.
Single Lattice—External Lacing Steel Poles.								
$2\frac{3}{4} \times 2\frac{3}{4} \times \frac{3}{16}$-inch L Poles.								
20	5⅝	9⅝	316	2,440		4	2,910	
25		10⅝	389	2,090		5	2,440	
30		11⅝	462	1,860		5½	2,120	
35		12⅝	534	1,700		6	1,910	
40		13⅝	607	1,580		6½	1,730	
45		14⅝	680	1,490		6½	1,630	
$3 \times 3 \times \frac{1}{4}$-inch L Poles								
20	6½	10½	441	3,840		4	4,500	
25		11½	544	3,290		5	3,840	
30		12½	647	2,900		5½	3,200	
35		13½	750	2,630		6	2,950	
40		14½	831	2,430		6½	2,700	
45		15½	955	2,290		6½	2,490	
$3\frac{1}{2} \times 3\frac{1}{2} \times \frac{5}{16}$-inch L Poles.								
20	7⅜	11⅜	630	6,130		4	7,430	
25		12⅜	779	5,200		5	6,130	
30		13⅜	917	4,580		5½	5,320	
35		14⅜	1,077	4,130		6	4,660	
40		15⅜	1,226	3,800		6½	4,240	
45		16⅜	1,374	3,570		6½	3,890	
$4 \times 4 \times \frac{3}{8}$-inch L Poles								
20	8¼	12¼	824	9,250		4	11,500	
25		13¼	1,020	7,770		5	9,420	
30		14¼	1,216	6,800		5½	8,020	
35		15¼	1,412	6,100		6	7,080	
40		16¼	1,607	5,620		6½	6,400	
45		17¼	1,804	5,220		6½	5,840	

Note.—Safe load = Failure load/factor of safety.

$$= \frac{\text{Failure load}}{2{\cdot}5} \text{ (for this country).}$$

Compiled by Walter Bates, Steel Corporation.

CALCULATIONS FOR STAYS.

For unbalanced tension due to curve or angle in the line we have

$$2\mathrm{T}\frac{\sin\phi}{2} \quad \text{(lb.)}.$$

Moment due to the unbalanced tension (for one crossarm, or one level) is

$$n\mathrm{L}_a\left(\frac{\mathrm{T}\sin\phi}{2}+\frac{\mathrm{T}\cos\phi}{2}\right) \quad \text{(ft.-lb.)}$$

where

n = number of conductors at same height above ground, in feet.
T = tension in stay-wire, in pounds.
ϕ = vertical angle between stay and pole.
L_a = effective lever arm above ground-line, in feet.
$= \mathrm{Q}/p_c$.
$\mathrm{Q} = \mathrm{T}_a\mathrm{L}_a$.
T_a = tension at effective point of application of load, in pounds.
p_c = wind pressure on conductors, L_a distance above ground, pounds.
$= pn(l'+l'')/2$ (lb.) (see p. 79).
$l'l''$ = adjacent spans, in feet.

Unbalanced conductor tension for combined *angle and terminal* is

$$\frac{\mathrm{T}\sin\phi}{2}+\frac{\mathrm{T}\cos\phi}{2} \quad \text{(lb.)}.$$

Tension on stay-wire is

$$\frac{\mathrm{L}_a\mathrm{T}_a}{h'\sin\phi}$$

where h' = vertical height above ground to attachment of stay on pole, in feet.

$$\sin\phi=\frac{1}{\sqrt{1+\left(\frac{h'}{h''}\right)^2}} \quad \text{(see } \sin\phi \text{ and } \cos\phi\text{, p. 109).}$$

h'' = horizontal distance at ground-line from pole to where stay enters the ground, in feet.

Vertical tension in pole due to stay-wire is

$$T'' \cos \phi \quad \text{(lb.)},$$

where T'' = tension in stay, in feet.
ϕ = angle between pole and stay.

Tension in stay where stay-wire is attached at point of resultant load at angle in line is

$$R/\cos \phi \quad \text{(lb.)},$$

where R = resultant load to be balanced (see also p. 117).

TABLE XII.

CONSTANTS USED FOR STAYING POLES.

Angle ϕ.	$\frac{1}{\tan \phi}$.	$\frac{1}{\sin \phi}$.	$\frac{1}{\cos \phi}$.	$2 \sin \frac{\phi}{2}$.
5 degrees	11·430	11·474	1·004	0·087
10 ,,	5·670	5·759	1·015	0·174
15 ,,	3·732	3·864	1·035	0·261
20 ,,	2·750	2·924	1·064	0·347
25 ,,	2·144	2·366	1·103	0·433
30 ,,	1·732	2·000	1·155	0·518
35 ,,	1·428	1·743	1·221	0·601
40 ,,	1·191	1·556	1·305	0·684
45 ,,	1·000	1·414	1·414	0·765
50 ,,	0·839	1·305	1·556	0·845
55 ,,	0·700	1·221	1·743	0·923
60 ,,	0·577	1·155	2·000	1·000
65 ,,	0·466	1·103	2·366	1·075
70 ,,	0·364	1·064	2·924	1·147
75 ,,	0·267	1·035	3·864	1·217
80 ,,	0·176	1·015	5·759	1·286
85 ,,	0·086	1·004	11·474	1·351
90 ,,	0·000	1·000	Infinity.	1·414

CALCULATION OF POLE FOUNDATIONS.

Maximum pressure for wood pole set *in earth* is

$$\frac{12T(H+0{\cdot}66l)}{0{\cdot}8l^2d_g} \quad \text{(lb./sq. in.)}.$$

Maximum pressure for wood or steel pole set *in concrete* is

$$\frac{12T(H+0{\cdot}66l)}{l^2 d_c} \quad \text{(lb./sq. in.)}$$

where T = resultant pull on pole, in pounds.
H = height from ground-line at which pull acts, in inches.
l = length of pole in ground, in inches;
d_c = diameter or width of concrete at ground-line (assuming a form like the embedded-base in fig. 13), in inches;
d_g = diameter of pole at ground-line, in inches.

Ordinary soil may be taken at a unit loading of 1·75 tons/sq. ft. For foundation compression stresses, the range is approximately:

For loam	2,000 to 3,500	lb./sq. ft.
,, clay	4,500 ,, 10,000	,,
,, sand	9,000 ,, 14,000	,,
,, hard-pan . . .	18,000 ,, 27,000	,,

The overturning resistance of an "A" wood frame *with ordinary earth* foundation is approximately 40,000 lb./ft.

In designing a *square* footing, the resistance of footing to uplift is

$$r = W'(a^2b + 2ab^2\ 0{\cdot}577 + k').$$

For a *rectangular* footing the resistance to uplift is

$$r = W'(acb + [a+c]b^2\ 0{\cdot}577 + k').$$

For a *round* footing the resistance to uplift is

$$r = W'(x + y + k'),$$

where W' = weight of cubic unit of earth = 90 to 100 lb./cub.-ft. for earth = 140 lb./cub.-ft. for concrete.
a = width of one side.
b = depth below ground-level.
c = width of one side of rectangular form.
$k' = \pi b^3/9$.
$x = \pi a^2 b/4$.
$y = \pi a b^2/3{\cdot}464$.

Where the foundations are poor, additional horizontal timber baulks in wooden-pole construction are added to the base to increase the ground resistance to uplift. For wooden "A" frames (commonly called poles) the effective weight of the foundations can easily, for straight runs, be 50 per cent. greater than the greatest uplifting force. The requirements for resistance to uplift in footings for this country was given as 2·5, neglecting that it depends on the location, soils, and many other factors.

As a guide to safe line construction it is helpful to tabulate the calculated stresses for the different items of construction and compare them with the allowable stresses required by *Regulations*, such as:

Conductor:

Ultimate strength of conductor . . . . . lb.
Elastic limit of conductor . . . . . . ,,
Stress for maximum allowable loading (Regulations) . ,,
Conductor span . . . . ft.
Maximum allowable, if any . . . . . . ,,
Conductor separation . . . (horizontal) in.
,, ,, ... (vertical) ,,
Minimum allowable by Regulations . (horizontal) ,,
,, ,, ,, . (vertical) ,,
Conductor overhead clearance above ground:
Clearance at maximum temperature in still air . . ft.
Clearance required by Regulations . . . . . ,,

Bending Moment of Pole:

Safe loading for required height, and top and ground-line diameter . . . . ft.-lb.
Loading required by Regulations . . . . . ,,

Crossarm:

Stress in direction of line which single crossarm will safely withstand . . . . lb.
Stress for double crossarm (ditto) . . . . . ,,
Maximum loading in direction of line when one conductor breaks . . . . ,,

Pins:

Stress which one pin will safely withstand . . . . ,,
Stress which two pins on terminal pole will safely withstand . . . . ,,
Lateral stress required by Regulations . . . . ,,

Insulators:

Stress which one insulator will safely withstand	lb.
Stress which two insulators in series will safely withstand	,,
Minimum dry flash-over	kV

Stay:

Safe loading (unbalanced tension)	lb.
,, ,, at curve	,,
,, ,, at combined curve and terminal	,,
,, ,, in stay	,,
,, ,, in pole due to stay	,,

Stay-Insulators:

Stress which one insulator will safely withstand	,,
Minimum dry flash-over	kV

ELECTRICAL CALCULATIONS.

The loss of energy in a circuit during the year is dependent upon the load factor of the load carried; in calculating line losses an appropriate full account is not always taken of the load factor and of other conditions affecting the total losses. For a new line and load, it is rarely possible to get close accuracy. The amount deducted (as annual line expense) from the gross income is made up largely of factors that are fixed regardless of the amount of power transmitted, but the chief question is the proper value of these different variables which involve depreciation, maintenance, taxes, and interest on the money actually spent on the line.

For distribution lines in general, knowing the distance and power loss (or assuming the latter), the size of conductor for a three-phase circuit can be found from:

$$R = 0{\cdot}333(\text{kW loss})/I^2 \quad \text{(ohms)},$$

wherein R is the total ohmic resistance at a given temperature, the range of R being 0° C. to 50° C. (see Table XIII.). Dividing the value of R by the distance will give the resistance per unit length (feet, yards, or miles, as the case may be) of single conductor, and when this is known the size of conductor can be obtained directly from Tables XV. or XVI.

The total kW loss is found from

$$p = 3I^2R$$

per unit length of line, and the power loss by

$$(4453Pl)/(E^2A \cos \phi^2).$$

The percentage power loss is

$$p' = (p/P)100.$$

In calculating for voltage drop it is usual to specify circuit factors in terms of delivered load and general receiving end conditions, and to reduce the delivered power—in terms of delivered voltage and load power factor—to load current values. These are given in the calculations to follow. If the voltage drop is assumed, it will usually be found that the size of conductor falls between two commercial standard sizes, one or the other of which must be chosen, and therefore calculations are usually necessary for a chosen size of conductor in order to determine the voltage drop for the size of conductor available or to be used. This can be found from fig. 15.

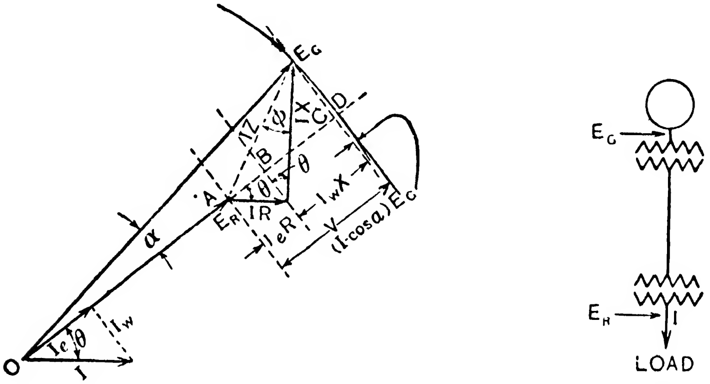


Fig. 14.—Vector diagram of a simple transmission line showing relation between generator and receiver voltage to neutral. (These relations are typical of the overhead power distribution lines of this country.)

Table XIII.

Copper Conductor Ohmic Resistance for the Range of Temperatures met with in Practice.

Temperature.	Stranded.	Solid.
	Ohms per Square-inch Section.	
122° F.=50° C.	0·0504	0·0494
95° F.=35° C.	0·0478	0·0468
77° F.=25° C.	0·0461	0·0451
59° F.=15° C.	0·0442	0·0433
32° F.= 0° C.	0·0415	0·0407

Fig. 15 should be found useful for d.c. or a.c. overhead lines as well as underground (insulated) cable systems, when it is desired to know:

The voltage drop, the power loss, or the size of conductor.

TABLE XIV.

RELATIVE CONDUCTOR REQUIREMENTS, BASED ON EQUAL PERCENTAGE OHMIC VOLTS DROP (e), WHICH IS THE MORE COMMON CONDITION IN DISTRIBUTION PRACTICE.

System.	(For Equal Voltage between Phase or Line Conductors.)				
	(1.)	(2.)	(3.)	(4.)	(5.)
D.c. : 2-wire	E/2	PR/E	$2PR/E^2$	100	100
„ 3-wire ($n=0{\cdot}5$)	E/2	PR/E	$2PR/E^2$	100	125
Single-phase for cos $\phi=1{\cdot}0$:					
2-wire	E/2	PR/E	$2PR/E^2$	100	100
3-wire ($n=0{\cdot}5$)	E/2	PR/E	$2PR/E^2$	100	125
Two-phase for cos $\phi=1{\cdot}0$:					
4-wire	E/2	PR/2E	PR/E^2	50	100
Quarter-phase : 5-wire ($n=0{\cdot}5$)	E/2	PR/2E	PR/E^2	50	112·5
Three-phase for cos $\phi=1{\cdot}0$:					
3-wire	E/1·732	PR/1·732E	PR/E^2	50	75
4-wire ($n=0{\cdot}5$)	E/1·732	PR/1·732E	PR/E^2	50	87·5
„ ($n=1{\cdot}0$)	E/1·732	PR/1·732E	PR/E^2	50	100
	(For Equal Voltage between Phase Conductors and Earth.)				
D.c. : 2-wire	E/2	PR/E	$2PR/E^2$	100	100
„ 3-wire ($n=0{\cdot}5$)	E	PR/2E	$PR/2E^2$	25	31·3
Single-phase for cos $\phi=1{\cdot}0$:					
2-wire	E/2	PR/E	$2PR/E^2$	100	100
3-wire ($n=0{\cdot}5$)	E	PR/2E	$PR/2E^2$	25	31·3
Two-phase for cos $\phi=1{\cdot}0$:					
3-wire	E	PR/E	$PR/2E^2$	50	85·3
4-wire	E/2	PR/2E	$PR/2E^2$	50	100
Quarter-phase : 5-wire for cos $\phi=1{\cdot}0$	E	PR/4E	$PR/4E^2$	12·5	28·2
Three-phase for cos $\phi=1{\cdot}0$:					
3-wire	E/1·732	PR/1·732E	PR/E^2	50	75
4-wire ($n=0{\cdot}5$)	E	PR/3E	$PR/3E^2$	16·7	29·2
4-wire ($n=1{\cdot}0$)	E	PR/3E	$PR/3E^2$	16·7	33·3

(1) = voltage between any phase conductor and earth.
(2) = voltage drop between any phase conductor and earth for equal total delivered load P.
(3) = voltage drop for equal percentage volts drop.
(4) = relative area of outer conductor for equal percentage volts drop.
(5) = relative total weight of conductors.
n = area of neutral divided by area of phase or line conductor.
cos ϕ = power factor ; thus, divide power loss values by $\cos^2\phi$, and respective volts drop and economic size values by cos ϕ.

Knowing the size and length of conductor, the power and the total load current, the power loss can be obtained on looking up the ohmic resistance values, R, given in the tables. More often than not it is the voltage drop which forms the basis of calculations for a.c. aerial power lines. Such systems are not only dependent on the value of P, but they are also dependent on the magnetic flux in and surrounding the line conductors, the system frequency, the size, arrangement, and spacing of the conductors, the line current, and the load power factor. The e.m.f. set up in the conductor is proportional to the line current, I; the magnetic flux density is greatest at the surface of the conductor. Neglecting proximity and skin effects, the fundamental formulæ for the induced e.m.f. (total effective inductance) per mile of single conductor is given by

$$L=0{\cdot}0804673+0{\cdot}7411536\log_{10} s/r \text{ (millihenries)}$$

or

$$L=(80{\cdot}4673+741{\cdot}1536\log_{10} s/r)\times 10^{-6} \text{ (henries).}$$

This induced counter e.m.f. is proportional to the frequency, f, and the current, I; for a symmetrical three-phase or for a single-phase aerial line the total counter e.m.f. per mile of single conductor is given by

$$IX=2\pi fIL=6{\cdot}283fIL \text{ (volts).}$$

The values in fig. 15 are based on the following formulæ for inductive reactance (volts per ampere) per mile of single conductor:

$$X=2\pi f(0{\cdot}08047+0{\cdot}0741\log_{10} s/r) \text{ (ohms).}$$

It is assumed here that the conductors for the different phase conductors of a three-phase circuit are transposed so that the voltage drop is the same for each phase. If the conductors are irregularly spaced, the voltage drop due to the inductive reactance will not be the same in each phase conductor. For an irregular flat or triangular—not an equilateral triangular—spacing, the average reactance per conductor or phase conductor is found from:

$$X=2\pi f\left(80+741{\cdot}1\log_{10}\frac{\sqrt[3]{abc}}{r}\right)\times 10^{-6} \text{ (ohms),}$$

where $s=\sqrt[3]{abc}$, and a, b, c are respectively the irregular spacings.

For a three-phase regular flat or vertical spacing, with the same spacing, a, between the two outside and the middle line conductors, the average reactance per conductor is given by

$$X = 2\pi f\left(80 + 741 \cdot 1 \log_{10} \frac{1 \cdot 26a}{r}\right) \times 10^{-6} \text{ (ohms)},$$

where $s = 1 \cdot 26a$.

The arrangement of conductors offering the least reactance is an equilateral triangle, and the one offering the most overhead clearance (assuming all other conditions the same) is that with the base of triangle perpendicular; (E) on p. 60 offers most.

For unsymmetrical arrangement of line conductors, the inductive reactance is higher, longer crossarms may be required, and in some cases longer poles required. Moreover, the effective (or average) spacing usually represents a fractional number of inches. Fig. 15 meets this trouble, as it gives values of inductive reactance, X, for any odd or fractional value of spacing in inches.

In finding the line resistance-volts (IR cos ϕ), little time is spent, but it is different when we have to determine the reactance-volts (IX sin ϕ). There are certain short-cut methods which one might apply; for instance, on careful study of fig. 15, it will be evident that the value of X for a given frequency, f, is fixed for a constant value of the ratio s/d (or $s/2r$), and that, for a given percentage difference in the value of s, there is a constant value of X for a given value of f, regardless of the diameter of conductor d.

As regards the ohmic resistance values, to find the value of R for any given size of conductor, simply follow the vertical line for given size of conductor until it intersects the oblique line corresponding to the given kind of conductor and metal (solid, stranded, copper, aluminium), when to the right we obtain directly the value R in ohms, or IR in resistance-volts per ampere. Inversely, we may also find the size of conductor when the power loss or the ohmic resistance has been assumed. This part of fig. 15 can be used for:

Obtaining the size of conductor when the power loss is given;

Obtaining directly the voltage drop per ampere in d.c. lines;

Obtaining the ohmic resistance for stranded commercial sizes of conductors.

As stranded conductor is more generally used, the sizes are given in square inch sectional area values. The value of reactance, X, is for a 50-cycle system; for any other frequency, f, multiply the values by the corresponding frequency coefficient given at the bottom of fig. 15, or, calculate it from:

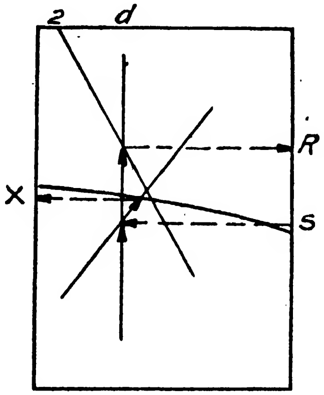
$$X' = X(f'/f) \text{ (ohms)},$$

here X' = inductive reactance for desired frequency, f'.

f' = desired frequency; f = frequency = 50 cycles per second.

X = inductive reactance for a 50-cycle system.

The values of X are quite simple to obtain, and will be found the most valuable part of the figure. The arrangement as presented is a development from the slide-rule—the diagonal lines forming the moving element of the slide-rule. This part of the diagram can be used for:



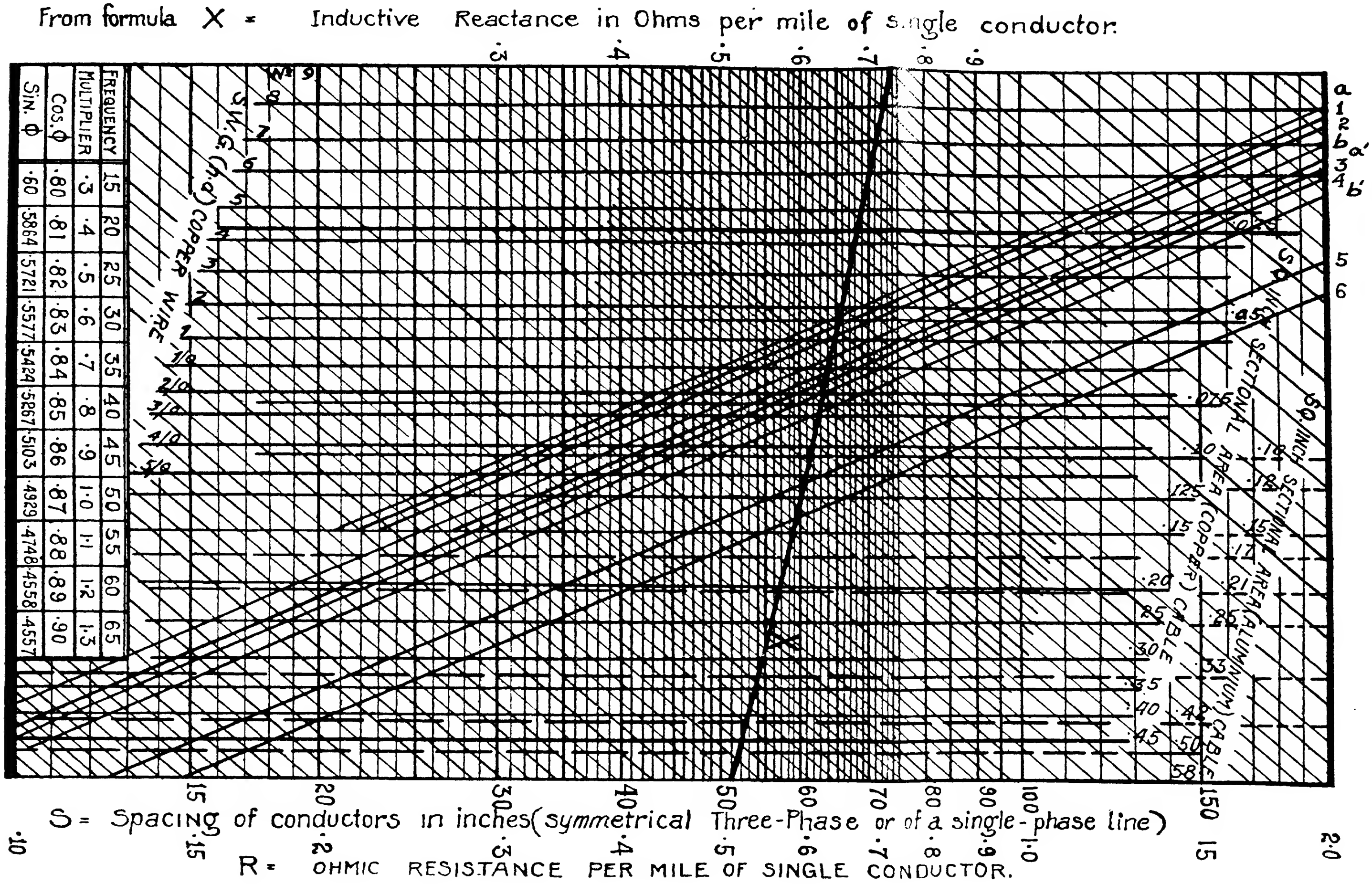
To *find resistance*, follow size of Conductor *d* to intersection with *a—b*, or *1—4*, thence to scale of R on right.

To *find reactance*, follow line from S on right to meet size of Conductor *d*, thence pass along diagonal to intersection with X-line, and read value of X on left-hand scale.

d = Size of conductor (vertical line) in L.S. gauge and sq. in. values.
R = Ohmic resistance, per mile of single conductor.
S = Spacing of *two* conductors; in inches between centres.
X = Inductive reactance in ohms, or reactance-volts per ampere, per mile of single conductor at 50 cycles per second.
2 = Conductor metal, for temperature value in °C. and °F. respectively.

KEY DIAGRAM TO FIG. 15A.

> Obtaining directly the inductive reactance, X, for any spacing of the conductors in inches or in fractions thereof. This is a most desirable requirement in view of the fact that regular flat, or vertical, or an irregular or/and unsymmetrical arrangement of the conductors of any phase circuit will most often call for an odd or fractional value for the effective spacing, hence the conductor separation in intervals of 1 in. or in fractions of 1 in. is desirable in certain work, and these X values should prove useful.
>
> Obtaining self-induction, L, by dividing the values given in the diagram by $6{\cdot}283f = 314{\cdot}16$.



FREQUENCY	15	20	25	30	35	40	45	50	55	60	65
MULTIPLIER	·3	·4	·5	·6	·7	·8	·9	1·0	1·1	1·2	1·3
COS. ϕ	·80	·81	·82	·83	·84	·85	·86	·87	·88	·89	·90
SIN. ϕ	·60	·5864	·5721	·5577	·5424	·5267	·5103	·4929	·4748	·4558	·4557

Fig. 15.

Obtaining the values of L or X, or IX per ampere, for commercial sizes of solid or stranded conductors.

Obtaining values of inductive reactancé, X, for any frequency by multiplying values of X by respective frequency co-efficients given.

To use the inductive reactance part, start from the right side and move along the horizontal logarithmic line for given value, *s*, to the intersection of vertical line (plotted to logarithmic scale) for size of conductor, see key diagram on p. 102. At the point where these two values intersect, move along parallel to the diagonal lines to a point crossing the X lines, when to the left and horizontal to the meeting of the X line and the diagonal line we obtain the required value of inductive reactance, X.

Fig. 14 represents a simple circuit. The current, voltage, and power factor are measured at the receiving end. The actual current, I, lags behind the receiver voltage by the angle, ϕ, whose cosine is the power factor; it causes a drop through the resistance, R, in phase with it, as shown, *i.e.* IR is parallel to I, and causes a drop through the reactance 90° out of phase with I, the current lagging with respect to IX, as shown; *i.e.* IX is at right angles to I. The vector, E_g, indicates the required voltage at the supply end of the line. From Fig. 14 we see that:

$$e' = E_g - E_r = I_e R \quad I_w X \text{ (nearly)},$$

that

$$AB = IR \cos\phi = I_e R,$$
$$BC = IX \sin\phi = I_w X,$$

and

$$CD = E_g - E_g \cos x = E_g(1 - \cos a).$$

The quantity $E_g(1 - \cos a)$ is so small that, in practice, it is usually neglected. Therefore, for voltage drop we obtain:

$$e = I_e R + I_w X,$$

where I_e = energy component of I.
I_w = wattless component of I.
a = angle between E_g and E_r.
R = resistance in ohms between E_g and E_r.
X = reactance in ohms between E_g and E_r.
E_g = sending end voltage to neutral.
E_r = receiving end voltage to neutral.

As the prevailing conditions of aerial a.c. lines are for lagging power factor ranging from 80 to 90 per cent., the simple and sufficiently accurate formulæ for voltage drop to neutral is given by:

$$\mathrm{IR}\cos\phi+\mathrm{IX}\sin\phi \quad \text{(volts).}$$

For a three-phase 3-wire line, the total voltage drop is:

$$e=\sqrt{3}\mathrm{I}(\mathrm{R}\cos\phi+\mathrm{X}\sin\phi) \quad \text{(volts).} \quad \text{(See p. 257.)}$$

For a single-phase 2-wire line

$$e=2\mathrm{I}(\mathrm{R}\cos\phi+\mathrm{X}\sin\phi).$$

The voltage at the generating or sending end being

$$\mathrm{E}_g=\mathrm{E}_r+e,$$

but

$$\mathrm{E}_g=\sqrt{[(\mathrm{E}_r\cos\phi+\mathrm{IR})^2+(\mathrm{E}_r\sin\phi+\mathrm{IX})^2]}$$

and voltage regulation

$$(\mathrm{E}_g-\mathrm{E}_r)/(\mathrm{E}_r 100).$$

The single-phase system is the simplest form of electric circuit and requires the minimum number of conductors, and therefore offers the minimum initial cost for distribution, but the feeders require 25 per cent. more copper than the equivalent three-phase system. The size of conductor for a given load and drop (three-phase) is but one-half what it would be for a single-phase circuit, and, for conductors of equal size (which is often the basis of assumption), the distance may be doubled for the same drop as compared with a single-phase circuit. In the case of an unbalanced three-phase 4-wire circuit the effect of the drop on the neutral conductor must be taken into consideration, as shown in the following calculations. However, compensators are very often employed in each phase conductor to care for voltage drop, and only the ordinary calculations are required as the compensator can compensate for the effects of voltage drop in the neutral.

The regulation of a single-phase, or a symmetrical polyphase, system may be calculated by considering one conductor *only*, assuming a neutral which has zero resistance and zero reactance, as the return conductor.

The three-phase 3-wire system may be treated as a single-phase system transmitting one-half the power.

The single-phase 2-wire circuit consists of two conductors with constant voltage maintained between the conductors, the load being connected in parallel across the circuit. For computing voltage drop and power loss, the ohmic resistance and the reactance of both conductors must be considered, that is:

and $$\left.\begin{array}{l}R=2R'l\\ X=2X'l\end{array}\right\}\text{(ohms)},$$

and the power transmitted is

$$P=E_rI\cos\phi\quad\text{(watts)},$$

or $$(E_rI\cos\phi)/1000\ \text{(kW)}.$$

The power loss is $$p=I^2R\ \text{(watts)}$$

or $$2R'I^2l=2(P^2/E_r\cos\phi)l\quad\text{(watts)}.$$

Then, percentage power loss is

$$p\text{ per cent.}=100(2R'lP^2)/(E_r{}^2\cos^2\phi\ P)=(200P^2R'l)/(E_r{}^2\cos^2\phi),$$

which is the amount in per cent. of delivered power.

The voltage drop is expressed

$$\sqrt{[(E_r\cos\phi_r+2R'lI)^2+(E_r\sin\phi_r+2X'lI)^2]}-E_r,$$

and the percentage voltage drop is

$$e\text{ per cent.}=\left(\frac{\sqrt{[(E_r\cos\phi_r+2R'lI)^2+(E_r\sin\phi_r+2X'lI)^2]}}{E_r}-1\right)100,$$

which is the drop in per cent. of delivered voltage.

For a three-phase 3-wire system, if the load is equally balanced on the three phases, the neutral carries no current, and a fourth conductor (if one is installed) could be removed, making a three-phase 3-wire system. Assume that the voltage between any two line conductors of a three-phase 3-wire system, for delta connection, equals E′, while the line current is I″, then

$$E'=\sqrt{3}E''\ \text{(for the \textit{star} connection)}$$

and

$$I''=\sqrt{3}I'\ \text{(for the \textit{delta} connection)},$$

and the power transmitted is

$$3E_r''I''\cos\phi_r\quad\text{or}\quad 3E_r'I'\cos\phi_r\ \text{(watts)}.$$

For balanced loads,

$$\cos\phi''=\cos\phi'$$

and the power transmitted is

$$\sqrt{3}E_r'I'' \cos \phi_r \text{ (watts)}.$$

The power loss is given by

$$3I''^2R'l=(P^2R'l)/(E_r'^2 \cos^2 \phi_r) \text{ (watts)},$$

and the percentage loss is given by

$$(100P^2R'l)/(E_r^2 \cos^2 \phi_r) \text{ (watts)},$$

which is seen to be just one-half that for a single-phase system.

Voltage drop (on each phase) for the *star* connected system may be computed by adding the impedance drop on one conductor vectorially to E″, because

$$E_r'=\sqrt{3}E_r'' \quad \text{and} \quad E_s'=\sqrt{3}E_s''.$$

The voltage drop for star is given by

$$\sqrt{[(E_r'' \cos \phi_r+R'lI'')^2+(E_r'' \sin \phi_r+X'lI'')^2]}-E_r'',$$

and the voltage drop for delta is

$$\sqrt{[(E_r' \cos \phi_r+\sqrt{3}R'lI'')^2+(E_r' \sin \phi_r+\sqrt{3}X'lI'')^2]}-E_r'.$$

The percentage voltage drop is given by

$$e=[(e''/E_r'')-1]100$$

and

$$e=[(e'/E_r)-1] \text{ (for full load delivered; see also p. 257)}.$$

Or, in terms of supply end values,

$$e \text{ per cent.}=\left(1-\frac{\sqrt{[(E_s \cos \phi_s-RI)^2+(E_s \sin \phi_s-XI)^2]}}{E_s}\right)100,$$

which is in per cent. of E_s, where

$$E_s=\sqrt{[(E'' \cos \phi+RI)^2+(E'' \sin \phi+XI)^2]}.$$

Voltage drop in terms of delivery end is

$$e=\left(\frac{\sqrt{[(E \cos \phi+\sqrt{3}RI)^2+(E \sin \phi+\sqrt{3}XI)^2]}}{E}-1\right)100,$$

where E = voltage between conductors.

The *three-phase* 4-*wire* system is equivalent to three single-phase systems supplied from the same source, the voltages in each phase being 120° out of phase with each other. One conductor is used as a common return for the entire system. The current passing through the neutral is equal to the vector sum of the currents in the three phases but in opposite phase. The power transmitted equals the sum of the powers in each of the three phases; that is to say:

$$\left.\begin{array}{l} P = E_r'I' \cos \phi_r' \\ \quad + E_r''I'' \cos \phi_r'' \\ \quad + E_r'''I''' \cos \phi_r''' \end{array}\right\} \text{(watts)}$$

and for a balanced load

$$\begin{aligned} P &= 3E_rI \cos \phi \text{ (watts)} \\ &= (3E_rI \cos \phi)/1000 \text{ (kW)}. \end{aligned}$$

The loss of power in a three-phase 4-wire system equals the loss in the *four* conductors, which is

$$\begin{aligned} p_x' &= I'^2R'l + I''^2R'l + I'''^2R'l + I_n^2R'l \\ &= R'l(I'^2 + I''^2 + I'''^2 + I_n^2) \text{ (watts)}. \end{aligned}$$

For balanced loads the total power loss is

$$p' = 3I^2R'l \quad \text{or} \quad l(3E_rI \cos \phi) \text{ (watts)}$$

wherein

$$I' = I'' = I'''; \qquad I_n = \text{zero}.$$

The average voltage drop, if the neutral current is comparatively small, will be approximately that obtained by computing each phase separately, neglecting the neutral and averaging the drops obtained; or by computing as a balanced 3-wire system with the current the average of the currents in the three phases. If the load is equally balanced the neutral carries no current, and obviously could be removed as mentioned above. However, there often are unbalanced loads, and such conditions become more complex. Assume that I′, I″, and I‴ each have a current differing in ampere value but have the same power factor for all phases; then, taking I′ as a line of reference to determine components of I″ and I‴ in phase with I′, we have

$$I'' \cos \phi = I_a; \qquad I''' \cos \phi = I_b$$

and

$$I'' \sin \phi = I_A; \qquad I''' \sin \phi = I_B$$

then

$$\left.\begin{array}{l} I' - I_a - I_b = I_x' \text{ in phase with } I' \\ I_A'' - I_B''' = I_x'' \text{ at } 90° \text{ behind } I' \end{array}\right\} \textit{components} \text{ of } -I_n$$

$$I_n = I_x'' - I_x'$$

at

$$\tan^{-1}(I_x''/I_x') \text{ ahead of } I.$$

If the voltage at source is symmetrical and balanced, and equals normal voltage E to neutral, then the power at source is

$$P = E \cos \phi (I' + I'' + I''') \quad \text{(watts).}$$

The power loss is

$$p_x' = R'l(I'^2 + I''^2 + I'''^2 + I_n^2) \quad \text{(watts).}$$

Neglecting the drop in neutral, voltage drop by the approximate method, is drop in phase

$$(1) = I'(R \cos \phi + X \sin \phi) = e',$$

volts drop in phase

$$(2) = I''(R \cos \phi + X \sin \phi) = e'',$$

volts drop in phase

$$(3) = I'''(R \cos \phi + X \sin \phi) = e''',$$

the average volts drop being

$$e = (e' + e'' + e''')/2.$$

The voltage drop in neutral is

$$e_n = I_n(R \cos \phi + X \sin \phi).$$

The percentage voltage drop is

$$e \text{ per cent.} = (e/E_r)100.$$

For unbalanced loads we may also calculate current in the neutral conductor as follows:

Let total power transmitted equal $P = P' + P'' + P'''$.

And let voltage per phase to neutral equal E′, E″, and E‴, respectively.

Since the power factor is assumed the same in each phase, the neutral current is the *vector sum* of I′, I″, I‴, that is

$$P' = E'I' \cos \phi; \quad P'' = E''I'' \cos \phi; \quad \text{and} \quad P''' = E'''I''' \cos \phi,$$

and

$$I' = P'/E' \cos \phi; \quad I'' = P''/E'' \cos \phi; \quad \text{and} \quad I''' = P'''/E''' \cos \phi.$$

Then

$$\begin{array}{rl} I'\times 1{\cdot}0 = & I' \\ -I''\times 0{\cdot}5 = & -\tfrac{1}{2}I'' \\ -I'''\times 0{\cdot}5 = & -\tfrac{1}{2}I''' \\ \hline & I_y \end{array} \qquad \text{and} \qquad \begin{array}{rl} I'\times 0 = & 0 \\ -I''\times 0{\cdot}866 = & -0{\cdot}866I'' \\ I'''\times 0{\cdot}866 = & 0{\cdot}866I''' \\ \hline & I_z \end{array}$$

and

$$I_n=\sqrt{I_y^2+I_z^2},$$

where

E_r = voltage between conductors at load end.
I = load current in amperes.
P = power transmitted.
R = total resistance of circuit in ohms.
R' = unit resistance per foot of circuit in ohms.
l = distance from source to load end.
$p'p$ = power loss of delivered load.
p per cent. = percentage power loss of delivered load.
X = total inductive reactance in circuit in ohms.
X' = unit inductive reactance per foot of circuit in ohms.
E_s = voltage at tap of branch. supply point or source, to neutral.
e = average volts drop.
e per cent. = percentage volts drop.
e_n = voltage drop in neutral.
$\cos\phi$ = power factor.
$\cos\phi_r$ = power factor at load end.
$\cos\phi_s$ = power factor at source.
e' = delta voltage drop.
e'' = star voltage drop.

Necessary equivalent *sine* and *cosine* values are:

Cos φ.	*Sin φ.*	*Cos φ.*	*Sin φ.*
·97	·243	·86	·510
·96	·279	·85	·526
·95	·312	·84	·542
·94	·341	·83	·557
·93	·367	·82	·572
·92	·391	·81	·586
·91	·414	·80	·600
·90	·436	·79	·613
·89	·455	·78	·625
·88	·475	·77	·638
·87	·493	·76	·650

TABLE XV.

RESISTANCE, WEIGHT, AND BREAKING LOAD OF BARE H.D. COPPER CONDUCTORS AND APPROXIMATE EQUAL CONDUCTIVITY ALUMINIUM CONDUCTORS.

COPPER CONDUCTORS.

Nominal Area in Square Inches.	Stranded Conductors.	Diameter in Inches.	Weight per 1000 Yards. (Lb.)	Breaking Load. (Lb.)	Standard Resistance in Ohms at 60° F.	
					Per 1000 Yards.	Per Mile.
0·025	3/·104	0·224	300·6	1,518	0·9887	1·74
0·05	3/·147	0·317	600·5	2,914	0·4943	0·87
0·075	3/·180	0·388	900·3	4,250	0·3294	0·5789
0·10	7/·136	0·408	1,196 0	5,872	0·2469	0·4345
0·15	7/·166	0·498	1,782 0	8,526	0·1656	0·2914
0·20	7/·193	0·579	2,408·0	11,270	0·1224	0·2155
0·25	7/·215	0·645	2,989·0	13,800	0·09861	0·1736
0·30	19/·144	0·72	3,646·0	17,370	0·08126	0·143
0·40	19/·166	0·83	4,845·0	22,640	0·06111	0·1076
0·50	19/·185	0·925	6,017·0	27,720	0·04919	0·08657
0·60	37/·144	1·008	7,103·0	33,830	0·04175	0·07348
0·75	37/·162	1·134	8,989·0	42,160	0·03297	0·05803

ALUMINIUM CONDUCTORS.

Nominal Area in Square Inches.	Stranded Conductors.	Diameter in Inches.	Weight per 1000 Yards. (Lb.)	Breaking Load. (Lb.)	Standard Resistance in Ohms at 60° F.	
					Per 1000 Yards.	Per Mile.
0·0417	3/·133	0·2866	148·08	1,118	1·0086	1·775
0·0835	3/·187	0·403	292·74	1,975	0·5102	0·898
0·1252	7/·151	0·453	444 0	3,254	0·3344	0·5885
0·1670	7/·174	0·522	589·5	4,163	0·2518	0·4432
0·2505	19/·133	0·665	936·9	7,080	0·1591	0·280
0·3345	19/·151	0·755	1,207·5	8,830	0·1234	0·2172
0·4170	19/·167	0·835	1,476·9	10,480	0·1009	0·1776
0·5010	19/·183	0·915	1,773·6	12,200	0·08403	0·1479
0·6680	19/·212	1·06	2,380·2	15,430	0·06261	0·1102
0·8350	37/·170	1·19	2,982·0	21,030	0·05003	0·08805
1·0020	37/·187	1·309	3,608·4	24,600	0·04135	0·07278
1·2520	37/·208	1·456	4,464·0	29,200	0·03342	0·05882

Table XVI.

Copper Wire—Solid—Bare (Hard-drawn).

Normal Area (Square Inch).	Diameter (Inch).	Resistance of 60° F. (15·6° C.)		Weight in Lb.		Ultimate Tensile Strength (Lb.).
		Per 1000 Yards.	Per Mile.	Per 1000 Yards.	Per Mile.	
0·175	0·472	0·1402	0·2467	2023	3561	8,544
0·15	0·437	0·1636	0·2879	1734	3052	7,500
0·125	0·399	0·1964	0·3456	1446	2546	6,431
0·100	0·357	0·2455	0·4320	1157	2037	5,310
0·075	0·309	0·3280	0·5773	867·1	1526	4,129
0·05	0·252	0·4937	0·8699	576·7	1015	2,875
0·03631	0·215	0·6787	1·1954	419·8	739	2,142
0·03269	0·204	0·7540	1·3270	377·9	664	1,943
0·02926	0·193	0·8425	1·4828	338·3	595	1,750
0·02688	0·185	0·9172	1·6233	310·8	547	1,621
0·02545	0·180	0·9689	1·7052	294·2	518	1,540
0·025	0·178	0·9909	1·7440	287·7	506	1,515
0·02164	0·166	1·140	2·0064	250·2	440	1,324
0·02061	0·162	1·197	2·1067	238·3	419	1,266
0·01815	0·152	1·360	2·3936	209·8	369	1,123
0·01697	0·147	1·454	2·5590	196·2	345	1,056
0·01629	0·144	1·515	2·6664	188·3	331	1,016
0·01453	0·136	1·699	2·9903	168·0	296	912

For the same distance, load, loss, and voltage drop, a line consisting of copper conductors is best; some of the advantages are:

For equal voltage stress to earth and equal delivered load and loss, a line consisting of copper offers the smallest size of conductor (see also p. 132).

For the same delivered load and voltage drop, copper conductors are subjected to the least wind and the least ice loading (see also p. 115).

For distribution lines in general there is a wide and frequent change in conductor stress due to temperature changes, and, for a given span length, copper conductors more satisfactorily meet this hazard as there is relatively less variation, etc.

For the same delivered load and voltage drop, copper conductors have the greatest advantages from elasticity and expansion standpoints (see also p. 128).

TABLE XVII.

CONSTANTS FOR HARD-DRAWN STRANDED COPPER CONDUCTORS UPON WHICH TABLES FOR SAG CALCULATIONS CAN BE BASED.

(This is the table to use for loading and strengths because all constants are based on the Electricity Commissioners' requirements and the Engineering Standards Association specifications.)

Nominal Area. Square Inch.	Strands and Diameter.	Ultimate Strength of Wire before Stranding (Lb.).[1]	Calculated Strength in Lb.[2]		Ultimate Strength of Wires (Lb./Sq. In.).	Calculated Strength (Lb./Sq. In.).	Resultant Loading. W. (Lb.) per Foot of Length.[3]
			Total.	Allowable.			
0·75	37/·162	1266	42,158	21,079	62,100	56,210	4·177
0·60	37/·144	1016	33,832	16,916	63,000	56,387	3·563
0·50	19/·185	1621	29,260	14,630	61,000	57,280	3·162
0·40	19/·166	1324	23,395	11,697	61,950	58,490	2·730
0·30	19/·144	1016	17,952	8,976	63,000	59,840	2·280
0·25	7/·215	2142	14,244	7,122	59,600	56,976	2·019
0·225	7/·204	1934	12,860	6,430	60,000	57,155	1·915
0·20	7/·193	1750	11,638	5,819	60,650	58,190	1·810
0·175	7/·180	1540	10,206	5,103	61,250	58,320	1·690
0·15	7/·166	1324	8,805	4,402	61,950	58,700	1·571
0·125	7/·152	1123	7,468	3,734	62,600	59,744	1·451
0·10	7/·136	912	6,065	3,032	63,400	60,650	1·342
0·075	3/·180	1540	4,481	2,240	61,250	59,750	1·257
0·05	3/·147	1056	3,073	1,536	62,850	61,460	1·127
0·025	3/·104	550	1,600	800	64,700	64,000	0·984

Based on the British Electricity Commissioners' Values for

[1] Ultimate strength of wire before stranding.

[2] Calculated strength after allowing for a reduction factor for ultimate strength of each wire before stranding, *i.e.* 90 per cent. for 37 wires; 93 per cent. for 19 wires; 95 per cent. for 7 wires; and 97 per cent. for 3 wires.

Total vertical weight of cable and ice per foot of length $= 1{\cdot}24d_1(d+d_1)$ in pounds.

Weight due to wind pressure $= \frac{8(d+2d_1)}{12}$ in pounds.

[3] Weight of wires, wind-load, and ice-coating for W.

TABLE XVIII.

COPPERWELD WIRE—SOLID—BARE (HARD-DRAWN).

Size A.W.G. (B. & S.).	Diameter (Inch).	Breaking Load (Lb.).	Average Weight in Lb.		Average Resistance in Ohms at 68° F.			
					1000 Feet.		Mile.	
			1000 Feet.	Mile.	30 Per Cent.	40 Per Cent.	30 Per Cent.	40 Per Cent.
0000	0·460	9850	585	3089	0·165	0·124	0·871	0·655
000	0·410	8280	467	2466	0·208	0·156	1·098	0·824
00	0·365	6850	370	1954	0·262	0·197	1·38	1·04
0	0·325	5700	293	1547	0·331	0·248	1·75	1·31
1	0·289	4800	231	1220	0·421	0·316	2·22	1·67
2	0·258	4000	184	971	0·531	0·398	2·80	2·10
3	0·229	3200	146	771	0·670	0·503	3·54	2·66
4	0·204	2650	116	615	0·844	0·633	4·46	3·34
5	0·182	2200	92	485	1·06	0·799	5·60	4·23
6	0·162	1800	73	385	1·34	1·01	7·08	5·33
7	0·144	1450	58	308	1·69	1·27	8·92	6·71
8	0·128	1200	40	242	2·13	1·60	11·3	8·45
9	0·114	970	37	195	2·69	2·02	14·2	10·7
10	0·102	800	29	154	3·39	2·55	17·9	13·5
11	0·091	645	23	121	4·28	3·21	22·6	16·9
12	0·081	520	18	96	5·39	4·05	28·5	21·4
13	0·072	415	14·38	76	6·80	5·11	35·9	27·1
14	0·064	330	11·55	61	8·58	6·44	45·3	34·0

(Compiled by Copperweld Steel Co. for copperweld wire.)

TABLE XIX.

STEEL-CORED ALUMINIUM CONDUCTORS (*British Sizes*).

Equivalent Normal Copper Area.	Over-all Diam. of Conductor.	Calculated Area of Aluminium.		Stranding and Wire Diameter.		Resistance at 60° F. in Ohms.	Total Weight of Conductor.	Approximate Ultimate Strength of Conductor.	
Sq. In.	In.	Sq. In.	Cir. Mil.	Alum.	Steel.	Per Mile.	Lb. per Mile.	Lb.	Lb./Sq. In.
0·025	0·281	0·04039	51,423	6/·0935	1/·0935	1·736	383·4	2,181	45,400 ✓
0·03	0·306	0·04806	61,198	6/·102	1/·102	1·458	456·3	2,547	44,500
0·04	0·354	0·06433	81,906	6/·118	1/·118	1·089	610·7	3,409	44,500
0·05	0·396	0·08050	102,496	6/·132	1/·132	0·8685	764·2	4,106	42,800 ✓
0·06	0·432	0·09580	121,976	6/·144	1/·144	0·7298	909·4	4,886	42,800
0·07	0·471	0·11387	144,991	6/·157	1/·157	0·6136	1,081·0	5,586	41,200
0·075	0·483	0·11975	152,474	6/·161	1/·161	0·5835	1,137·0	5,874	41,200
0·08	0·498	0·12731	162,091	6/·166	1/·166	0·5489	1,208·0	6,061	40,000
0·09	0·531	0·14474	184,290	6/·177	1/·177	0·4825	1,374·0	6,819	39,600
0·10	0·558	0·15983	203,508	6/·186	7/·062	0·4369	1,415·0	7,387	40,400
0·125	0·624	0·19988	254,497	6/·208	7/·069	0·3492	1,770·0	9,134	39,700
0·15	0·714	0·24032	305,989	30/·102	7/·102	0·2915	2,592·0	15,238	50,400
0·175	0·770	0·27950	355,869	30/·110	7/·110	0·2506	3,015·0	17,722	50,400
0·20	0·826	0·32165	409,533	30/·118	7/·118	0·2178	3,469·0	20,394	50,400
0·225	0·875	0·36094	459,565	30/·125	7/·125	0·1939	3,893·0	22,524	49,600
0·25	0·924	0·40250	512,478	30/·132	7/·132	0·1737	4,341·0	24,716	48,800
0·30	1·022	0·49241	626,957	30/·146	7/·146	0·1420	5,311·0	30,237	48,800
0·35	1·099	0·56938	724,959	30/·157	7/·157	0·1227	6,142·0	33,525	46,800
0·40	1·176	0·65197	830,113	30/·168	7/·168	0·1072	7,032·0	37,072	45,200
0·45	1·239	0·72371	921,450	30/·177	7/·177	0·09651	7,806·0	40,787	44,700
0·50	1·251	0·80338	1,022,897	54/·139	7/·139	0·08703	7,114·0	36,330	39,200
0·60	1·368	0·96067	1,223,162	54/·152	7/·152	0·07274	8,507·0	41,881	37,900
0·75	1·530	1·20166	1,529,996	54/·170	7/·170	0·05816	10,641·0	51,038	36,900

TABLE XX.

STEEL-CORED ALUMINIUM CONDUCTORS (*British Sizes*).

Equivalent Copper Section (Sq. In.)	Stranding.		Ratio of Aluminium.		Virtual Constants.			Weight per Ft. per Sq. In. (Lb.)
	Steel.	Alum.	to Steel *Section.*	to Steel *Weight.*	Modulus (e) (Lb./Sq. In.)	Coefficient of Expansion (a) (per °F.)	Ultimate Stress (Lb./Sq. In.)	
0·09	1	6	6	2·1	$12{\cdot}85\times10^{6}$	$11{\cdot}0\times10^{-6}$	43,000	1·51
0·09 –0·125	7	6	7·72	2·7	$12{\cdot}85\times10^{6}$	$11{\cdot}38\times10^{-6}$	39,500	1·45
0·125–0·45	7	30	4·29	1·5	$13{\cdot}8\times10^{6}$	$10{\cdot}48\times10^{-6}$	49,000	1·62
0·45 and over	7	54	7·72	2·7	$12{\cdot}3\times10^{6}$	$11{\cdot}38\times10^{-6}$	39,500	1·45

TABLE XXI.

STRANDED ALUMINIUM CONDUCTORS (*British Sizes*).[1]

Equivalent Normal Copper Area.	Over-all Diameter of Conductor.	Stranding and Wire Diameter.	Calculated Area of Conductor.		Resistance at 60° F. in Ohms.	Total Weight of Conductor.	Approximate Ultimate Strength of Conductor.	
Sq. In.	In.		Sq. In.	Cir. Mil.	Per Mile.	Lb. per Mile.	Lb.	Lb./ Sq. In.
0·02	0·254	3/·118	0·03216	40,954	2·178	297·2	859	27,000
0·025	0·284	3/·132	0·04025	51,248	1·737	259·3	996	25,000
0·03	0·310	3/·144	0·04790	60,988	1·460	308·6	1,185	25,000
0·04	0·330	7/·110	0·06540	83,273	1·071	418·9	1,724	27,000
0·05	0·366	7/·122	0·08045	102,438	0·8699	515·4	2,042	26,000
0·06	0·402	7/·134	0·09706	123,583	0·7203	621·7	2,369	25,000
0·07	0·432	7/·144	0·11209	142,712	0·6238	718·0	2,736	25,000
0·075	0·447	7/·149	0·12001	152,799	0·5826	768·7	2,929	25,000
0·08	0·462	7/·154	0·12820	163,217	0·5451	821·1	3,067	24,500
0·09	0·492	7/·164	0·14538	185,107	0·4807	931·3	3,478	24,000
0·10	0·519	7/·173	0·16178	205,980	0·4317	1036·0	3,791	23,500
0·125	0·579	7/·193	0·20134	256,357	0·3467	1290·0	4,620	23,500
0·15	0·633	7/·211	0·24066	306,411	0·2899	1542·0	5,404	23,000
0·175	0·695	19/·139	0·28297	360,288	0·2471	1819·0	6,776	25,000
0·20	0·745	19/·149	0·32515	413,992	0·2150	2090·0	7,786	24,500
0·225	0·785	19/·157	0·36099	459,624	0·1936	2321·0	8,471	24,500
0·25	0·830	19/·166	0·40356	513,829	0·1732	2594·0	9,470	23,750
0·30	0·915	19/·183	0·49046	624,466	0·1424	3153·0	11,157	23,500
0·35	1·985	19/·197	0·56838	723,685	0·1228	3654·0	12,793	23,500
0·40	1·055	9/·211	0·65203	830,192	0·1070	4192·0	14,364	23,000
0·45	·127	37/·161	0·73888	940,763	0·0946	4755·0	16,609	24,500
0·50	1·176	37/·168	0·80453	1,024,358	0·0869	5177·0	18,085	24,500
0·60	1·281	37/·183	0·94561	1,215,441	0·0732	6143·0	20,802	23,750
0·75	1·442	37/·206	1·20965	1,540,166	0·0577	7784·0	25,804	23,250

Neglecting the supports, which we may assume for the purpose of comparison to possess relatively equal strength, it is not generally realised that, for a given set of loading conditions and size and kind of conductor for distribution lines in general, the tension for all temperature changes will decrease with increasing span length. This is important when deciding on the kind of conductor metal to use, because of the weakening at the points of support with certain conductor metals—the lighter conductor offering still greater hazard due to effects from wind.

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[1] An aluminium conductor approximately 1·34 times the sectional area of a given copper conductor will carry the same current for the same temperature rise.

TABLE XXII.

HIGH STRENGTH, HIGH CONDUCTIVITY COPPER-ALLOY CONDUCTORS.*

(*See p.* 180 *for sag and tension values.*)

Area, Weight, Resistance, Elastic Limit, Breaking Strength, and Tensile Strength.

Temperature 20° C. or 68° F. Density 8·89 grams per cm.^{3}
† Average Conductance of Wire 77·32 per cent. of that of Standard Annealed Copper Wire of the same Dimensions.
Minimum Conductance of Wire 75·0 per cent. of that of Standard Annealed Copper Wire of the same Dimensions.
Weight and Resistance Increased 2 per cent. to allow for Cabling.

Size of Cable. Circular Mils or B. & S. Gauge.	Area of Cable. (Square Inch.)	‡ Equivalent Area Hard-drawn Copper Cable 97·5 per cent. I.A.C.S. Circular Mils or B. & S. Gauge.	Number of Wires in Cable.	Diameter of Wires. (Mils).	Diameter of Cable. (Mils).	Weight per 1000 Feet. (Lb.)	‡ Resistance Average per 1000 Feet. (Ohms).	§ Elastic Limit Average per Cable. (Lb.)	Breaking Strength Minimum per Cable. (Lb.)	Tensile Strength Minimum per Square Inch. (Lb.)
630,500	0·4952	500,000	37	130·5	914	1,947	0·02170	21,990	36,640	74,000
567,400	0·4457	450,000	37	123·8	867	1,752	0·02411	20,060	33,430	75,000
504,400	0·3961	400,000	37	116·8	818	1,557	0·02712	17,830	29,710	75,000
500,000	0·3927	396,500	37	116·2	813	1,544	0·02736	17,670	29,450	75,000
450,000	0·3534	356,900	37	110·3	772	1,389	0·03010	16,120	26,860	76,000
441,300	0·3466	350,000	19	152·4	762	1,363	0·03100	14,970	24,960	72,000
400,000	0·3142	317,200	19	145·1	726	1,235	0·03420	13,760	22,930	73,000
378,300	0·2971	300,000	19	141·1	706	1,168	0·03617	13,190	21,990	74,000
350,000	0·2749	277,600	19	135·7	679	1,081	0·03909	12,210	20,340	74,000
315,200	0·2476	250,000	19	128·8	644	973·3	0·04340	11,110	18,570	75,000
300,000	0·2356	237,900	19	125·7	629	926·3	0·04561	10,600	17,670	75,000
266,800	0·2096	4/0	19	118·5	593	823·8	0·05128	9,430	15,720	75,000
250,000	0·1963	198,300	19	114·7	574	771·9	0·05473	8,950	14,920	76,000
4/0	0·1662	3/0	19	105·5	528	653·3	0·06466	7,580	12,630	76,000
3/0	0·1318	2/0	19	94·0	470	518·1	0·08153	6,090	10,150	77,000

Size of Cable. A.W.G. or B. & S. Gauge.	Area of Cable. (Square Inch.)	‡ Equivalent Size Hard-drawn Copper Cable 97·5 per cent. I.A.C.S. B. & S. Gauge.	Number of Wires in Cable.	Diameter of Wires. (Mils).	Diameter of Cable. (Mils).	Weight per 1000 Feet. (Lb.)	‡ Resistance Average per 1000 Feet. (Ohms).	§ Elastic Limit Average per Cable. (Lb.)	Breaking Strength Minimum per Cable. (Lb.)	Tensile Strength Minimum per Square Inch. (Lb.)
0000	0·1662	000	7	173·9	522	653·3	0·06466	6,980	11,630	70,000
000	0·1318	00	7	154·8	464	518·1	0·08153	5,690	9,490	72,000
00	0·1045	0	7	137·9	414	410·9	0·1028	4,640	7,730	74,000
0	0·08289	1	7	122·8	368	325·8	0·1296	3,730	6,220	75,000
1	0·06573	2	7	109·3	328	258·4	0·1635	3,000	5,000	76,000
2	0·05213	3	7	97·4	292	204·9	0·2061	2,410	4,010	77,000
3	0·04134	4	7	86·7	260	162·5	0·2599	1,930	3,220	78,000
4	0·03278	5	7	77·2	232	128·9	0·3278	1,550	2,590	79,000
5	0·02600	6	7	68·8	206	102·2	0·4133	1,250	2,080	80,000

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* A conductor called "Hitenso BB" and manufactured by Anaconda Copper Mining Company, N.Y., U S.A.

† *Note.*—Resistance same as resistance of hard-drawn copper cable one B. & S. gauge number smaller.

‡ Area of hard-drawn copper cable having same resistance (or conductance) as that of this cable.
Per cent. conductivity of this copper alloy is 77·32 I.A.C.S.
,, ,, hard-drawn copper is 97·5 ,,

§ In this table the elastic limit is 60 per cent. of the minimum tensile strength. This elastic limit is approximately the Johnson elastic limit, which is that stress (lb. tension) at which the rate of deformation (elongation) is 50 per cent. greater than the initial rate of deformation.

TABLE XXIII.

TRANSVERSE AND VERTICAL LOADS IN LB./FT. ON STRANDED STEEL CABLE.

Diameter of Cable in Inches.	8 Lb. per Square Foot Wind on Wire plus ½-in. Radial Ice-coating.		8 Lb. per Square Foot Wind on Wire plus ¼ in. Radial Ice-coating.	
	Transverse.	Vertical.	Transverse.	Vertical.
$\frac{1}{4}$	0·835	0·579	0·512	0·276
$\frac{9}{32}$	0·854	0·635	0·521	0·321
$\frac{5}{16}$	0·874	0·701	0·541	0·380
$\frac{3}{8}$	0·917	0·830	0·584	0·490
$\frac{7}{16}$	0·959	0·916	0·626	0·613
$\frac{1}{2}$	1·000	1·126	0·777	0·750
$\frac{5}{8}$	1·083	1·499	0·750	1·085

For calculating the resultant stress on a pole *at an angle*, which stress should be taken up by a stay, the following figures are useful:—

Angle between the Conductors or Wires, both Sides of the Pole.	Resultant Stress on the Pole.	Angle between the Conductors or Wires, both Sides of the Pole.	Resultant Stress on the Pole.
ϕ in Degrees.	$R' = 2T \cos\left(\frac{\phi}{2}\right)$ Lb.	ϕ in Degrees.	$R' = 2T \cos\left(\frac{\phi}{2}\right)$ Lb.
30	R′=T×1·932	95	R′=T×1·351
45	,, ,, 1·848	100	,, ,, 1·286
50	,, ,, 1·813	110	,, ,, 1·148
55	,, ,, 1·774	120	,, ,, 1·000
60	,, ,, 1·732	130	,, ,, 0·846
65	,, ,, 1·687	140	,, ,, 0·684
70	,, ,, 1·638	150	,, ,, 0·518
75	,, ,, 1·587	160	,, ,, 0·348
80	,, ,, 1·532	170	,, ,, 0·174
85	,, ,, 1·475	175	,, ,, 0·086
90	,, ,, 1·414	180	,, ,, 0·000

The shorter the angle ϕ of the stay wire to the pole, the stronger must be the stay wire, and the greater the angle ϕ the greater will be the allowable total area of conductors. The usual angle given a stay wire ranges between 45 and 30 degrees. The resultant stress on the pole at a right-angle turn (90°) is equal to $R' = T \times 1{\cdot}414$ at 180° $R' = T$.

LOADS IN POUNDS PER LINEAR FOOT ON BARE STRANDED COPPER CABLE (*American Sizes*).

Size of Conductor, A.W.G. No. or Circular Mil. (*Stranded*).	Over-all Diameter in Inches.	11 Lb. per Sq. Ft. Wind on Wire + ¾-in. Ice.		8 Lb. per Sq. Ft. Wind on Wire + ½-in. Ice.		8 Lb. per Sq. Ft. Wind on Wire + ¼-in. Ice.		15 Lb. per Sq. Ft. Wind, no Ice.	Wire alone, no Ice.	12 Lb. per Sq. Ft. Wind, no Ice.	½ Ultimate Strength = Allowable Tension. Hard Drawn.
		Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	
500,000 C.M.	0·814	2·121	2·998	1·209	2·357	0·876	1·871	1·016	1·540	0·814	11,355
450,000 „	0·772	2·082	2·809	1·180	2·181	0·847	1·708	0·965	1·390	0·772	10,230
400,000 „	0·728	2·042	2·618	1·152	2·004	0·819	1·543	0·910	1·240	0·728	9,165
350,000 „	0·681	1·999	2·415	1·119	1·815	0·786	1·369	0·851	1·080	0·681	8,020
300,000 C.M.	0·630	1·953	2·223	1·087	1·629	0·754	1·210	0·786	0·926	0·630	6,930
250,000 „	0·575	1·902	2·018	1·050	1·441	0·717	1·029	0·718	0·772	0·575	5,805
0000	0·528	1·859	1·845	1·015	1·292	0·682	0·895	0·660	0·653	0·528	4,845
000	0·470	1·806	1·656	0·980	1·121	0·647	0·742	0·588	0·518	0·470	3,880
00	0·418	1·758	1·500	0·943	0·982	0·610	0·619	0·518	0·411	0·418	3,090
0	0·373	1·717	1·373	0·917	0·870	0·584	0·520	0·460	0·326	0·373	2,460
1	0·332	1·679	1·267	0·885	0·776	0·552	0·439	0·410	0·258	0·332	1,955
2	0·292	1·643	1·177	0·861	0·698	0·528	0·374	0·365	0·205	0·292	1,520
3	0·260	1·613	1·105	0·841	0·636	0·508	0·322	0·325	0·163	0·260	1,220
4	0·232	1·588	1·045	0·821	0·584	0·488	0·279	0·290	0·129	0·232	970
5	0·206	1·564	0·994	0·804	0·541	0·471	0·264	0·258	0·102	0·206	775
6	0·184	1·544	0·952	0·789	0·506	0·456	0·216	0·230	0·081	0·184	615
0000	0·460	1·797	1·770	0·973	1·238	0·640	0·862	0·575	0·641	0·460	4,070
000	0·410	1·750	1·591	0·940	1·075	0·607	0·713	0·512	0·508	0·410	3,360
00	0·365	1·709	1·443	0·910	0·940	0·577	0·594	0·456	0·403	0·365	2,760
0	0·325	1·673	1·323	0·883	0·833	0·550	0·499	0·406	0·320	0·325	2,260
Solid. 1	0·289	1·640	1·223	0·859	0·744	0·526	0·421	0·362	0·253	0·289	1,845
2	0·258	1·611	1·142	0·839	0·673	0·506	0·368	0·322	0·201	0·258	1,500
3	0·229	1·585	1·073	0·819	0·613	0·486	0·308	0·287	0·159	0·229	1,220
4	0·204	1·567	1·016	0·803	0·564	0·470	0·267	0·255	0·126	0·204	985
5	0·182	1·542	0·969	0·788	0·525	0·455	0·234	0·227	0·100	0·182	795
6	0·162	1·524	0·930	0·775	0·491	0·442	0·207	0·203	0·079	0·162	640
7	0·144	1·507	0·897	0·763	0·464	0·430	0·186	0·180	0·063	0·144	515
8	0·128	1·492	0·869	0·752	0·440	0·419	0·168	0·161	0·050	0·128	415

TABLE XXV.

LOADS IN POUNDS PER LINEAR FOOT ON BARE STRANDED ALL-ALUMINIUM CABLE (*American Sizes*).

Size of Conductor, Circular Mil.	Equivalent Copper Conductor Size.	Over-all Diameter in Inches.	11 Lb. per Sq. Ft. Wind on Wire +¾-in. Ice.		8 Lb. per Sq. Ft. Wind on Wire +½-in. Ice.		8 Lb. per Sq. Ft. Wind on Wire +¼-in. Ice.		15 Lb. per Sq. Ft. Wind, no Ice.	Wire alone, no Ice.	12 Lb. per Sq. Ft. Wind, no Ice.	½ Ultimate Strength = Allowable Tension.
			Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	
795,000 C.M.	500,000 C.M.	1·026	2·313	2·379	1·350	1·686	1·017	1·144	1·281	0·747	1·026	7,500
715,000 "	450,000 "	0·974	2·270	2·250	1·317	1·575	0·984	1·056	1·218	0·672	0·974	6,750
636,000 "	400,000 "	0·918	2·215	2·120	1·278	1·463	0·945	0·953	1·148	0·598	0·918	6,000
556,000 "	350,000 "	0·856	2·158	1·995	1·237	1·351	0·904	0·867	1·069	0·523	0·856	5,250
500,000 C.M.	314,500 C.M.	0·810	2·120	1·897	1·207	1·271	0·874	0·799	1·012	0·469	0·810	4,710
477,000 "	300,000 "	0·793	2·100	1·868	1·198	1·241	0·865	0·772	0·990	0·448	0·793	4,500
397,500 "	250,000 "	0·724	2·039	1·728	1·149	1·123	0·816	0·676	0·906	0·373	0·724	3,745
336,420 "	0000	0·657	1·972	1·605	1·104	1·023	0·771	0·598	0·822	0·316	0·657	3,175
300,000 C.M.	188,600 C.M.	0·621	1·945	1·538	1·080	0·969	0·747	0·553	0·776	0·282	0·621	2,825
266,800 "	000	0·586	1·912	1·475	1·057	0·917	0·724	0·511	0·732	0·251	0·586	2,520
211,950 "	00	0·522	1·855	1·369	1·014	0·826	0·681	0·439	0·653	0·199	0·522	1,985
167,800 "	0	0·464	1·800	1·331	0·975	0·763	0·642	0·380	0·581	0·158	0·464	1,590
133,220 C.M.	1	0·414	1·755	1·193	0·943	0·685	0·610	0·332	0·518	0·125	0·414	1,260
105,530 "	2	0·368	1·712	1·111	0·912	0·630	0·579	0·291	0·460	0·099	0·368	995
83,642 "	3	0·328	1·677	1·065	0·884	0·585	0·551	0·259	0·410	0·079	0·328	790

TABLE XXVB.

ALUMINIUM CABLE—STEEL REINFORCED—BARE (*American Sizes*).

Size of Conductor, Circular Mil.	Equivalent Copper Conductor Size.	Over-all Diameter in Inches.	11 Lb. per Sq. Ft. Wind on Wire +¾-in. Ice.		8 Lb. per Sq. Ft. Wind on Wire +½-in. Ice.		8 Lb. per Sq. Ft. Wind on Wire +¼-in. Ice.		15 Lb. per Sq. Ft. Wind, no Ice.	Wire alone, no Ice.	12 Lb. per Sq. Ft. Wind, no Ice.	½ Ultimate Strength = Allowable Tension.
			Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	Vertical.	Transverse.	
605,000 C.M.	380,500 C.M.	0·953	2·250	2·341	1·305	1·670	0·972	1·154	1·190	0·780	0·953	10,635
500,000 "	314,500 "	0·904	2·205	2·297	1·270	1·640	0·937	1·136	1·130	0·777	0·904	11,875
336,000 "	0000	0·741	2·055	1·900	1·160	1·290	0·827	0·836	0·927	0·528	0·741	8,100
266,800 "	000	0·633	1·960	1·586	1·090	1·040	0·757	0·619	0·794	0·344	0·633	4,692
0000	00	0·564	1·890	1·505	1·042	0·946	0·659	0·548	0·705	0·295	0·564	4,217
000	0	0·501	1·835	1·379	1·000	0·846	0·666	0·465	0·626	0·232	0·501	3,330
00	1	0·447	1·785	1·284	0·965	0·761	0·632	0·402	0·558	0·185	0·447	2,650
0	2	0·398	1·740	1·199	0·932	0·694	0·599	0·345	0·498	0·147	0·398	2,100
1	3	0·355	1·700	1·134	0·903	0·638	0·570	0·305	0·444	0·117	0·355	1,670
2	4	0·316	1·665	1·072	0·877	0·590	0·544	0·268	0·395	0·092	0·316	1,330
3	5	0·281	1·635	1·023	0·854	0·521	0·521	0·238	0·351	0·073	0·281	1,050
4	6	0·250	1·605	0·977	0·832	0·516	0·499	0·213	0·313	0·058	0·250	834
5	7	0·223	1·580	0·942	0·815	0·491	0·482	0·193	0·278	0·046	0·223	657
6	8	0·198	1·555	0·906	0·790	0·464	0·465	0·175	0·248	0·036	0·198	522

TABLE XXVI.

STEEL WIRE—STRANDED—GALVANISED.

Size.	Diameter (Inches).	Area (Square Inch).	Siemens-Martin.		High Tension.		Load per Lineal Foot (Vertical.)		Load per Lineal Foot. (Horizontal.) 8·0 Lb. per Sq. Ft. Cond. ½-in. Ice.	Maximum Load per Lineal Foot Resultant.	Angle of Resultant Load.	(eA) e = 29,000,000
			Ultimate Tension.	Allowable Tension.	Ultimate Tension.	Allowable Tension.	Dead.	Dead ½-in. Ice.				
$\frac{5}{8}$	0·6250	0·2356	19,000	9500	25,000	12,500	0·821	1·520	1·083	1·867	35° 30′	6,832,000
$\frac{9}{16}$	0·5625	0·1922	14,500	7250	21,100	10,550	0·668	1·329	1·042	1·689	38° 0′	5,574,000
$\frac{1}{2}$	0·5000	0·1443	11,000	5500	18,000	9,000	0·510	1·132	0·999	1·510	41° 30′	4,185,000
$\frac{7}{16}$	0·4375	0·1204	9,000	4500	15,000	7,500	0·415	0·998	0·958	1·383	43° 25′	3,492,000
$\frac{3}{8}$	0·3750	0·0832	6,800	3400	10,500	5,250	0·295	0·839	0·917	1·243	47° 50′	2,413,000
$\frac{5}{16}$	0·3125	0·0606	4,860	2430	8,100	4,050	0·210	0·715	0·875	1·130	50° 45′	1,757,000

TABLE XXVII.

COPPERWELD WIRE—SOLID—BARE (HARD-DRAWN).

Size A.W.G. (B. & S.) No.	Cross-section (Square Inch).	Allowable Tension in Lb.	Loads in Lb. per Lineal Foot.			Maximum Load in Plane of Resultant.	Young's Modulus of Elasticity.	Modulus Area (eA).
			Vertical Loads.		Horizontal Load. Wind Pressure 8 Lb. per Square Foot.			
			Dead Weight.	Dead Weight plus $\frac{1}{2}$-in. Radial Ice.				
0000	0·16620	4925	0·585	1·183	0·973	1·532	20,000,000	3,324,000
000	0·13180	4140	0·467	1·034	0·940	1·398	20,000,000	2,636,000
00	0·10450	3425	0·370	0·909	0·910	1·285	20,000,000	2,090,000
0	0·08290	2850	0·293	0·807	0·883	1·195	20,000,000	1,658,000
1	0·06573	2400	0·231	0·723	0·859	1·125	20,000,000	1,315,000
2	0·05213	2000	0·184	0·656	0·839	1·065	20,000,000	1,043,000
3	0·04134	1600	0·146	0·600	0·819	1·017	20,000,000	826,800
4	0·03278	1325	0·116	0·554	0·803	0·974	20,000,000	655,600
5	0·02600	1100	0·092	0·517	0·788	0·942	20,000,000	520,000
6	0·02062	900	0·073	0·485	0·775	0·914	20,000,000	412,400
7	0·01635	730	0·058	0·459	0·763	0·890	20,000,000	327,000
8	0·01297	600	0·046	0·437	0·752	0·870	20,000,000	259,400
9	0·01028	490	0·037	0·419	0·743	0·853	20,000,000	205,600
10	0·00815	400	0·029	0·403	0·735	0·838	20,000,000	163,100
11	0·00647	325	0·023	0·391	0·727	0·825	20,000,000	129,400
12	0·00513	260	0·018	0·379	0·721	0·815	20,000,000	102,600
14	0·00322	165	0·0116	0·362	0·709	0·796	20,000,000	64,400

(Compiled by Copperweld Steel Co. for copperweld wire.)

TABLE XXVIII.

COPPERWELD WIRE—STRANDED—BARE (HARD-DRAWN). (COPPERWELD.)

Actual Diameter (Inch).	No. and Sizes of Wires (A.W.G.).	Breaking Load (Lb.) (see Note).	Cross-section (Square Inch).	Allowable Tension (Lb.).	Loads in Lb. per Lineal Foot.				Young's Modulus of Elasticity. (*e*).	Modulus Area (*e*A).
					Vertical Loads.		Hor. Load. Wind Pressure 8 Lb. per Square Foot.	Max. Load in Plane of Resultant.		
					Dead Weight.	Dead Weight plus ½-in. Rad. Ice.				
1·274	37 No. 5	81,400	0·963	40,700	3·505	4·609	1·516	4·855		
1·134	37 No. 6	66,600	0·763	33,300	2·780	3·796	1·423	4·054		
1·008	37 No. 7	53,650	0·605	26,825	2·210	3·148	1·339	3·421		
0·896	37 No. 8	44,400	0·480	22,200	1·754	2·622	1·264	2·911		
0·910	19 No. 5	41,800	0·495	20,900	1·800	2·677	1·273	2·964		
0·810	19 No. 6	34,200	0·392	17,100	1·430	2·247	1·209	2·552		
0·772	19 No. θ	31,200	0·354	15,600	1·285	2·076	1·181	2·388		
0·720	19 No. 7	27,600	0·311	13,800	1·135	1·894	1·147	2·214		
0·681	19 No. θ	25,100	0·275	12,550	1·000	1·734	1·121	2·065		
0·640	19 No. 8	22,800	0·246	11,400	0·900	1·609	1·093	1·945		
0·612	7 No. 4	18,550	0·229	9,280	0·836	1·528	1·075	1·868	15,600,000	3,573,000
0·570	19 No. 9	18,430	0·195	9,220	0·724	1·383	1·047	1·735		
0·546	7 No. 5	15,400	0·182	7,700	0·663	1·304	1·031	1·662	16,100,000	2,912,000
0·523	7 No. θ	14,300	0·166	7,150	0·606	1·236	1·015	1·599	16,500,000	2,739,000
0·486	7 No. 6	12,600	0·144	6,300	0·526	1·139	0·991	1·510	17,000,000	2,434,000
0·465	7 No. θ	11,600	0·132	5,820	0·481	1·079	0·977	1·458	17,200,000	2,270,000
0·432	7 No. 7	10,160	0·114	5,080	0·418	0·998	0·955	1·381	17,800,000	2,029,000
0·414	7 No. θ	9,460	0·105	4,730	0·382	0·948	0·945	1·339	18,100,000	1,900,000
0·384	7 No. 8	8,400	0·0910	4,200	0·332	0·882	0·923	1·277	18,600,000	1,693,000
0·368	7 No. θ	7,780	0·0829	3,890	0·302	0·842	0·912	1·241	19,100,000	1,583,000
0·342	7 No. 9	6,790	0·0719	3,400	0·267	0·791	0·895	1·194	19,200,000	1,380,000
0·306	7 No. 10	5,600	0·0571	2,800	0·209	0·710	0·871	1·124	19,500,000	1,133,000
0·273	7 No. 11	4,550	0·0452	2,280	0·166	0·647	0·849	1·067	19,700,000	891,000
0·243	7 No. 12	3,640	0·0360	1,820	0·129	0·591	0·829	1·018	19,800,000	713,000
0·192	7 No. 14	2,310	0·0226	1,160	0·083	0·513	0·795	0·946	19,900,000	450,000

Note.—θ means special gauge wire (not in A.W.G. size). Coefficient of lineal expansion = 0·0000072 per °F. Breaking load of strand is taken as 90 per cent. of the sum of the breaking loads of the individual wires. (Compiled by Copperweld Steel Co. for copperweld wire.)

TABLE XXIX.

COPPERWELD-COPPER CABLES. WIRE TABLES AND LOADING TABLES.

19-Wire Concentric-lay Strand. (Each Cable composed of 7 Extra High Tensile Copperweld Wires surrounded by 12 Copper Wires.)

Wire Tables.							Loading Tables.						
Diameter Cable (Inch).	**Size of each of the 19 Wires (A.W.G.).**	**Breaking Load (Lb.) (see Note).**	Weight (Lb.).		Conductivity Equivalent (Cir. Mils of Copper).	Resistance (Ohms per 1000 Ft. at 68° F.).	Cross-section (Square Inch).	Allowable Tension (Lb.).	Loads in Lb. per Lineal Foot.				**Modulus × Area. (eA).**
			Per 1000 Ft.	Per Mile.					Vertical Loads.		Horizontal Load. Wind Pressure 8 Lb. per Sq. Ft.	Maximum Loads (in Plane of Resultant).[1]	
									Dead Weight.	Dead Weight plus ½-in. Rad. Ice.			
1·020	No. 4	50,200	2370	12,500	587,000	0·0180	0·621	25,100	2·370	3·318	1·347	3·581	9,936,000
0·910	No. 5	40,100	1883	9,942	468,000	0·0226	0·495	20,050	1·883	2·760	1·273	3·020	7,920,000
0·810	No. 6	32,000	1493	7,883	371,000	0·0285	0·392	16,000	1·493	2·305	1·207	2·602	6,272,000
0·720	No. 7	25,500	1180	6,230	294,000	0·0360	0·311	12,750	1·180	1·939	1·147	2·244	4,976,000
0·640	No. 8	21,280	931	4,916	233,000	0·0454	0·246	10,640	0·931	1·640	1·093	1·971	3,936,000
0·615	0·123 in.	18,690	859	4,535	211,600	0·0500	0·226	9,345	0·859	1·552	1·077	1·888	3,616,000
0·570	No. 9	16,200	738	3,896	185,000	0·0571	0·195	8,100	0·738	1·403	1·047	1·750	3,120,000
0·545	0·109 in.	14,700	675	3,564	167,800	0·0631	0·177	7,350	0·675	1·325	1·030	1·678	2,832,000
0·510	No. 10	12,900	591	3,120	146,000	0·0724	0·155	6,450	0·591	1·219	1·007	1·580	2,480,000

Young's Modulus of Elasticity (e) = 16,000,000. Coefficient of lineal expansion = 0·0000085 per °F.

NOTE.—***Breaking load*** **of each cable is rated at 90 per cent. of the sum of the breaking loads of its individual wires. This standard rating has been ound conservative for this type of cable.**

[1] **This is resultant of vertical loading due to dead weight of conductor plus ½-in. radial coating of ice and a horizontal transverse load due to 8 lb. per sq. ft. wind pressure.**

TABLE XXX.

THREE-PHASE MOTOR *Current* CAPACITY FOR DIFFERENT SIZES.

H.P.	Current in Amperes.		Average Efficiency (eff.).	Average Power Factor (cos ϕ).
	250 Volts.	400 Volts.		
150	310	193	0·93	0·90
140	288	180	,,	,,
130	268	167	,,	,,
120	248	155	,,	,,
110	226	142	,,	,,
100	206	129	,,	,,
90	186	116	,,	,,
80	166	103	,,	,,
75	154	97	,,	,,
70	146	91	,,	,,
60	126	78	,,	,,
50	104	65	,,	,,
45	102	64	0·92	0·85
40	90	57	,,	,,
35	80	49	,,	,,
30	68	42	,,	,,
25	56	35	0·90	0·83
20	46	28	,,	,,
15	36	23	,,	,,
12	30	18	,,	,,
10	24	15	0·80	0·82
7½	20	13	,,	,,
5	14	8	,,	,,
3	10	6	0·75	0·80
2	6	4	,,	,,

TABLE XXXI.

THREE-PHASE CURRENT PER KW FOR DIFFERENT VOLTAGES.

Voltage on Line.	cos ϕ = Power Factor.			
	100.	90.	80.	70.
220	2·628	2·92	3·28	3·75
390	1·482	1·646	1·852	2·117
440	1·314	1·46	1·64	1·877
3,300	0·175	0·194	0·219	0·25
6,600	0·875	0·973	0·109	0·125
10,000	0·0577	0·0641	0·0721	0·0825
22,000	0·0263	0·0292	0·0328	0·0375
33,000	0·0175	0·0194	0·0219	0·025

CHAPTER IV.

ASPECTS OF DISTRIBUTION LINE CONSTRUCTION.

Wood poles comprise a very large majority of the poles *universally* used for electricity distribution, hence the wood pole is given preference in this volume.

The theoretical strength of the wood pole is dependent on its diameter at or near the butt, the modulus of rupture of the timber used, and the taper of the pole. In practice we may have a condition where the taper is uniform such that the diameter at the ground-line is greater than the critical diameter, in which case the strength of the pole is independent of its height. In practice, general conditions are such that the strength of the pole is reduced until its diameter at the ground-line is less than the most critical diameter (which is somewhat higher than ground-line) and this strength varies, depending on height and diameter at ground-line.

Wooden crossarms also comprise the majority of arms *universally* used for overhead distribution lines; very much greater use should be made of the wood crossarm in this country. Where used, they should face on the opposite side of the pole from that on which the maximum strain acts. Where this is uncertain, as on straight runs where spans are equal and level, they should be faced alternately on succeeding poles, first in one direction and then in the other. The pins should stand perpendicular to the crossarm when fitted. The insulator should be screwed up tightly on the pin. On straight-line work, where top-groove insulators are used, the conductor should be placed in the top groove; for side-groove insulators, they should be placed on the side nearest the pole. On all curves the conductors should be tied on the side groove away from the strain so that the insulator takes it. At terminals or dead-ends and corners, double insulators or strain insulators are best. For straight-line construction, double insulators are not necessary for ordinary spans and h.d. copper conductors; where used, they provide greater safety than single insulators. At street corners double insulators are often necessary, but rarely if ever *along* streets.

The size of crossarm and the number of pins depend on the size, number, voltage, and span-length of conductors. The vertical spacing between the crossarms depends on the voltage, and the working space required; this latter is very important. Both wood and steel pins are used for secondary lines; the former has its advantages.

Secondary distribution conductors are usually covered with one, two, or three layers of cotton braid impregnated with a weather-resisting compound. This covering is intended to protect the line to some extent, such as against interruption to the continuity of service due to accidental contact with trees or certain foreign lines, etc. Bare tie-wire should not be used on covered conductors. In stringing conductors, the sighting method may be used for checking the dynamometer method.

For every location the length of span is one of the most important functions of safety—this applies to all lines whether for transmission or distribution of electricity. Thus, for a given line passing through villages and rural streets and roads, we may with greater security for safety to public either increase the loading conditions or decrease the span-length. The logical practice would be to fix the loading conditions for a given country or district ($\frac{3}{8}$", $\frac{1}{2}$", or $\frac{3}{16}$" ice and 8 lb. wind for this country, independent of the voltage whether it be 120 V or 22,000 V) and limit the maximum length of span according to the location and construction of the line.

THE overhead electric power line provides the most economical means of transmitting energy. From the time it was first known that electrical energy could be generated in one place and used at a distance, the pole line has proved one of the most useful engineering achievements. And, as regards the relative cost of insulation for overhead and underground service, with the overhead system one can afford to put in sufficient insulation to provide for the severest conditions, whereas for the same requirements in service conditions and for sufficient insulation, an underground system would cost very much more (see p. 1). With time, and as a given area becomes more and more densely populated, so will the underground system supersede and become a necessity, but overhead lines must first pave the way in a manner to satisfy present requirements and economy until a certain load and population density, etc. are built up.

Neglecting other important points already mentioned, what is required perhaps as much as anything else at the present time is :

> Power of compulsory expropriation for the purpose of installing overhead lines;
>
> Some power to make it possible to obtain joint occupancy of poles, and facilities for more use of roads or/and highways or/and cross-country wayleaves, quickly and on reasonable terms.

Overhead lines are often greatly hampered by inadequate wayleave, and in many cases easements can be obtained only on special conditions not always satisfactory or agreeable.

Because of the supposed danger of high-pressure lines, many unduly severe restrictions have been placed upon their construction in this country. It is true that if such lines are not *properly* constructed they may constitute a danger to the public, but there is nothing gained by enforcing construction standards much too severe.

A line, or an extension, may start out to deliver the whole of its power to the far end, and remain in that condition for many years ;

or, it may grow quickly into a distribution system in which more or less load is taken off along the line or extension as the case may be. The operating engineer usually desires the best construction and design. He is, nevertheless, usually compelled to consider closely the net revenue to be derived from any particular construction in a given number of years. The chief problems ever before him are: what will it cost? and, will it pay? He knows that no matter what the construction standards are, he must take the risks and be saddled with the responsibility of life and fire hazards and so forth.

Main-line service is exacting in every way, and the sub-stations or/and consumers connected therewith demand perfect service and can pay a higher price for reliability of service than can a secondary distribution line. Therefore, rural lines of this nature may call for a relatively less perfect service at less cost; of course, there is no definite measure of reliability, yet it is necessary that a rural line be so constructed and designed as to ensure adequate service. The Electricity Commissioners and the Electricity Authority may have quite different conceptions of adequate service—the former provide a set of loading conditions, etc. for hill and valley and every location and locality (for this country), while the latter desires to aim at proportioning the design and adopting safety factors to serve best the particular locality, climatic, and atmospheric conditions, population, etc., the principal object being to give a reliable service at low cost; the latter aim is truly wise policy. It is well to remember that to rural consumers it rarely occurs that irregular service is expensive at any price, but the opposite is always the case for a main-power line.

The weakest part of an overhead line may be the conductor, the insulator or its pin, the crossarm, the support or its foundation —generally it is the insulator, and this may be so whether the span be short, long, heavily or lightly loaded.

For a line of any voltage, if the cheapest, best, and most satisfactory operation is desired, the insulation of the conductors must be maintained. The appropriate insulator depends largely on climatic and atmospheric conditions existing in the particular district, *the kind of construction*, the conductor, size and stress, and the length of span. There is also the system and line to consider—choose that system and line giving best mechanical and best electrical polyphase conditions capable of giving satisfactory polyphase operation when a phase transformer is disabled and/or when a phase-conductor is broken. All these combined conditions give us the most ideal system and line operation engineers are looking for, the best of which (meeting these conditions) is the three-phase 4-wire system (see fig. 6, and figs. 32, 32A).

The function of the conductor itself is to transmit electrical energy, and its material and sectional area should be so chosen as to provide safe mechanical strength and best electrical efficiency for the maximum range of temperatures and maximum loadings. There is a correct ratio between the size and kind of conductor and permissible span-length for any given locality and given weather-loading conditions.

In choosing the conductor metal, consideration should be given to the question of possible corrosion of that material used in the particular locality. For instance, steel and aluminium near the sea, where moist salt air is brought in contact with them, will sometimes corrode so rapidly as to present an increasingly dangerous condition if ordinary maintenance is given them (see also p. 132).

It is sometimes stated that the variations in sag with changes of temperature will be more in aluminium than in copper. The increase in sag depends on the modulus of elasticity as well as the coefficient of expansion, and the effect of temperature is a function of their product. For conditions of equal conductivity (equal ohmic resistance), the relative values are:

$$\text{Aluminium} = 1{\cdot}64 \times 12{\cdot}6 \times 10^{-3} \times 9{\cdot}5^{10^6} = 196.$$
$$\text{Copper} = 1{\cdot}0 \times 9{\cdot}222 \times 10^{-6} \times 18^{10^6} = 166.$$

For equal resistance, a hard-drawn aluminium conductor has approximately 1·64 times the sectional area of a hard-drawn copper conductor of the same length.

In calculating loadings it is always assumed that the conductors are loaded uniformly throughout the span, and from span to span (see also p. 45). All spans are designed on the basis of being self-sustained with a uniform stress in the conductors, but only where adjacent spans are level and of uniform length is this condition strictly true in practice. Adjacent long and short spans, as also sloping spans, have the tendency at some time to take away (by reason of total gravity effect) from the short spans in the one case and from the top spans in the other case, thus increasing the sags in the longer spans and increasing the sag of the lower span. In making calculations it is better to take parts of the two adjacent spans, the proportion depending whether level or sloping (see p. 79).

In some cases, with unequal spans it may be better practice in stringing conductors—where overhead clearances are available—to allow relatively greater sag on the shorter spans than are usually given to other sections of the line having similar size, kind and disposition of conductors, and similar lengths of span, but with spans of equal length. That is, a certain proportioning of sags in the various spans may become necessary to permit of a better balancing of tension; this also is good reason for making the calculations proposed on p. 79.

Whether the span be short or long, each span will be subjected to the same maximum loading for the same size and kind of conductor metal, and for that loading, if strung to regulations, the tension will be the same; however, in the case of the longer spans, the stringing tension will be less than in the case of the shorter spans because of the greater sag, and it will be least at the time of the highest summer temperature in still air.

The smaller the diameter of the conductor, the greater will be the ice-load in comparison with the weight of the conductor itself. The wind pressure varies only as the diameter, but the weight varies as the square of the diameter ; therefore the relative effect will be much greater on small conductors than on large, and, in consequence of this condition, ice-loading on small conductors should *not* be the same as for large conductors. For 0·10 sq. in. copper conductor and less sizes, the same ice-loading conditions are less favourable (see fig. 16, curve 25 lb., wind without ice, and curve 8 lb., wind with $\frac{1}{4}$-in. ice. Also see fig. 11).

For equal overall diameter, the wind pressure and ice-loading on conductors and wires are approximately as follows:

> Favourable for copper conductors (which are often solid) as they collect less, obstruct less, and retain snow and sleet less, than either aluminium, steel, or iron ;
>
> Better for copper alloy than for aluminium, steel, or iron (see p. 67) ;
>
> Better for aluminium than for steel or iron of equal overall diameter, as, with time, the two latter collect more sleet and snow and offer greater resistance to wind; this is due to the fact that they rarely maintain the smooth surface and that innumerable rust points are formed, etc.;
>
> And, exceptionally favourable for copper conductors based on equal conductivity.

The spacing (or separation) of conductors depends on their disposition (or arrangement), and if this condition is not known we are unable to obtain or ascertain the proper spacing of the conductors as also the most economical size of pole to use. The minimum separation of conductors is largely a question of swinging, and their distance apart depends on the sag, *i.e.* span, weight of conductor, etc. For pressures up to about 25,000 volts, the spacing is independent of the voltage, as a few inches of air-gap provides ample insulation. The approximate sparking distances taken by needle-gap for different voltages are:

Voltage of Line.	Separation of Conductors in Inches.
5,000	0·225
10,000	0·470
15,000	0·725
20,000	1·000
25,000	1·300
30,000	1·625
35,000	2·000

In most cases of secondary lines, the object has been to choose the best arrangement of conductors independent of the inductive unbalancing; by doing so, head space and trouble from swinging and sagging are often avoided. Due to vertical arrangement (such as rack construction), instances are known of the upper conductor being loaded with birds or with snow to an extent sufficient to cause it to touch a conductor directly below. Also inaccurate sagging, slipping of the conductor from one span into another, and other causes, permit conductors and wires to get closer than originally anticipated in the design and construction.

Loading conditions should not be fixed for every line and all localities, they should respectively provide for factor of safety:

According to the design, and/or
According to the territory traversed, and/or
According to the construction, and/or
According to requirements of law, etc. and/or
According to whether a straight run or crossing is considered, and/or the length of span;

According to Regulations, the specified factors of safety are given on p. 68. A higher grade of construction is required for the higher voltage lines; such lines are invariably main power lines, and are inherently robust in construction. Starting the *higher* grade construction at, say, 325 volts is not justifiable.

Most rural lines are situated in more or less open country, and therefore subjected to greater wind pressure and greater ranges of temperature than urban lines. This is one reason why the New Zealand regulations provide for 18-lb. wind in rural areas and 12-lb. wind in urban areas. For a densely populated area less wind pressure can be expected than for an exposed and thinly populated zone, but there should be a higher grade of construction for the former condition; the New Zealand regulations meet this by limiting maximum span to 165 ft. The temperature should not be a fixed value for the entire country (mountain and valley) with or without maximum ice-loading, which should also be different, as also should factors of safety for supports be subjected to different loading conditions. The wind and the ice-loadings should be conservative for the particular district. It is commonly assumed that the wind is horizontal in direction, yet, if the line is on the side of a steep hill, the wind is more likely to have a considerable vertical component.

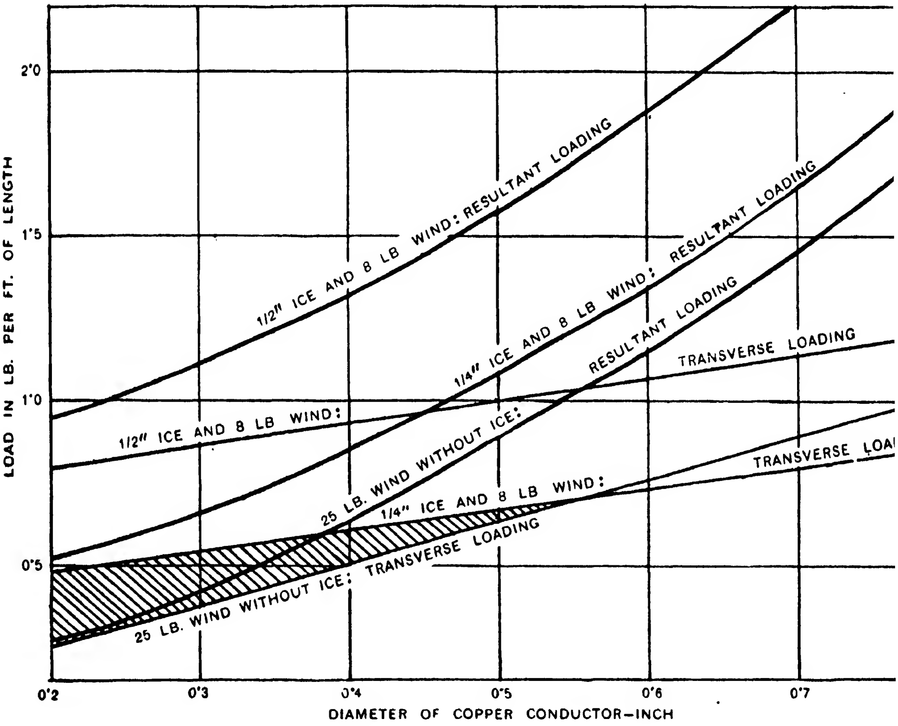

Fig. 16.—Conductor loading conditions, past and present.

Comparing this country with that of U.S.A., we have a wide margin of safety for equivalent specified loadings due to the relatively milder climatic conditions which obtain here. Experience has proved that in order to develop rural areas and give an economical and safe construction, the allowable stresses imposed must vary with the configuration and location (hill or valley, etc.), with the position of a support in a line (at a crossing or on a straight run), and that the minimum overhead clearances of conductors must be conservative. Experience has shown that for rural lines in particular, and all lines in general, there should be no necessity to impose improbable loads which are considered to be possible, although probably not on record or only occurring so infrequently —and in a particular locality, but not applicable to another—as to make their occurrence within any limited time very unlikely. Apart from knowledge of the amount and the effects of loads and resulting stresses, the right factor of safety depends on *kind of construction*, decay, corrosion, defects in materials, errors in designs, grade of workmanship, and so forth : and there is no reason to expect that such matters as materials, designs, and workmanship in this country are any worse, and decay and corrosion any greater than in other countries. The kind of construction requires modification, as pointed out.

The material and type of supports for the conductor, their insulating properties, and the disposition of the conductors, all should be chosen with due consideration to the district and the probable future growth and extensions.

The present minimum allowable conductor sizes and kind of metal for conductors in U.S.A. are of interest. For the different metals used (see *a*, *b*, *c*, and *d* below), it is shown that the minimum conductor size varies with the loading district, with the length of span, and with the grade of construction—all of which have been found necessary to facilitate safe and economical construction. For the medium loading district with which we are especially concerned, because it is practically the equivalent of the specified loading for this country, *i.e.* ¼-in. ice and 8-lb. wind, we have:

Span-Length in Feet.	Size of Conductor in Square Inches for Rural and Urban Areas.			
	(*a*).[1]	(*b*).[1]	(*c*).	(*d*).
150	0·013	0·013	0·066	0·0240
200	0·033	0·021	0·083	0·0383
300	0·033	0·033	0·083	0·0383
400	0·033	0·033	0·083	0·0383

where (*a*) = Copper, medium and hard drawn.
(*b*) = Copper-covered steel.
(*c*) = Aluminium without reinforcement.
(*d*) = Steel-reinforced aluminium.

[1] *Minimum* allowable size also favours *copper* conductors.

In the case of wood poles, the Bureau of Standards Rules of 1921 allowed a fibre stress equal to half the assumed ultimate strength. An improvement over these rules was made in 1927 which still further *favours construction in rural areas.* The allowable fibre stresses are varied according to the grade of construction and whether poles are located at crossings or in other places. For line construction in rural areas the allowable fibre stress is greater for all places, which means a smaller size of pole than formerly allowed. The loadings on conductor-supports are easier than the former rules; the *vertical* loads are the same (but these are of little import), and the transverse loadings for medium and light loading districts are much less, and these especially favour rural areas.

The allowable fibre stress for wood poles is 75 per cent. of the ultimate fibre stress for crossings, and 100 per cent. elsewhere than at crossings for grade C construction, which grade refers to supply lines of voltages ranging from 750 to 5000 volts between conductors. The transverse strength for this grade is not less than two-thirds of that required for grade B; this grade is for urban areas, and is superior. The minimum pole-top diameter for both grades of construction is 6 inches. The ultimate fibre stress values have not been altered, therefore the allowable fibre stresses for the different timbers are a decided advantage for rural lines in particular. For this country, with much less severe climatic conditions to contend with, 7800 lb./sq. in fibre stress and 3·5 for factor of safety are taken, or 2230 lb. allowable fibre stress for red fir creosoted poles. Therefore, assuming that the ultimate fibre stress value of red fir is reasonable, as also that of yellow pine and other timbers used for poles in the U.S.A., the relative percentage fibre stress allowable at the present time for *rural* areas and for voltages up to 750 volts is:

Location.	Relative Allowable Fibre Stress.	
	British.	American.
At crossings . . .	40 per cent.	100 per cent.
Elsewhere . . .	28·5 „	100 „

In other words, taking the British at 100 per cent., the American is 250 per cent. for crossings and 350 per cent. elsewhere. Also, in urban areas for voltages up to 7500 volts, the relative allowable fibre stress is:

Location.	Relative Allowable Fibre Stress.	
	British.	American.
At crossings . . .	57 per cent.	100 per cent.
Elsewhere . . .	50 ,,	100 ,,

That is to say, taking British at 100 per cent., the American is 175 per cent. at crossings, and 200 per cent. elsewhere than at crossings.

Note.—Dense yellow pine is 6000–6500, and western red cedar is 5000 lb./sq. in.

As with wood poles, the allowable unit stresses for steel poles and towers vary according to the grade of construction; the allowable stresses are also different for transverse strength and for longitudinal strength, which latter values are varied according to the different grades of construction, as well as according to whether crossings or other conditions are considered. The ultimate tensile stress is given as 50,000–65,000 lb./sq. in., and the yield-point not less than half the ultimate stress—equivalent to a factor of safety of 2·0. The slenderness ratios for compression members remain as before. A thickness of $\frac{1}{8}$ in. is not allowed; other thickness values remain as before, with the exception that where experience has shown rapid deterioration of galvanised material, $\frac{1}{4}$ in. is the minimum allowable thickness for main members of legs and cross-arms. According to the grade of construction and whether at a crossing or elsewhere, the allowable unit stresses range as follows:

Allowable Stresses for	Tension. (Lb./Sq. In.)	Compression. (Lb./Sq. In.)
Transverse strength . .	20,000–30,000	20,000–80 L/R to 30,000–100 L/R
Longitudinal strength in line	33,000	33,000–100 L/R
Longitudinal strength at crossings	30,000	30,000–100 L/R

The ability of a tower to resist its loading depends largely on properly designing and making the foundation and footing—the principal loads being horizontal. The allowable unit stresses on bolts and rivets are given as:

Unit.		For Transverse Strength. (Lb./Sq. In.)	For Longitudinal Strength. (Lb./Sq. In.)	
			Crossings.	Elsewhere.
Bolt :	Bending .	40,000–70,000	70,000	80,000
	Shear .	20,000–35,000	35,000	40,000
Rivet :	Bending .	36,000–60,000	60,000	66,000
	Shear .	18,000–30,000	30,000	33,000

The minimum horizontal separations between conductors are made a little greater in the revised U.S.A. rules; they are given in terms of sag. With reference to the vertical overhead clearances of conductors above ground, they remain the same as before, with the exception that for a span of 50 yd. the clearance increase *is less.* This, again, *favours rural lines* quite independently of the following values, which are for spans of 50 yd. and under:

Minimum Overhead Clearance for Line Pressures up to 750 Volts.		
Across Roads and Streets in Rural and Urban Areas.	*Along* Streets in Urban Areas.	*Along* Roads in Rural Areas.
18 feet.	18 feet.	15 feet.

Note.—The previous rules permitted this vertical overhead clearance of wires above ground for a maximum of 300 volts to earth, NOT 750 volts, between conductors, which is the present rule.

Much knowledge can be gained by discussing or analysing different safety and construction standards and practices; the object should be to seek for improvement and economy *with* safety. The most open-minded are those who gain by the experiences of others, who follow tried, tested, and proven good practice, who are willing to drop good things for better, who have and accept information *from anywhere*, provided it is sound, and who have the courage and strength to put through such improvements and to fight down all obstacles in the path of progress and development. At the present time there is much to be done, as will be gathered from the best practices in being, and those practices requiring radical changes.

In its endeavour to provide for safety, the common practice and the law of this country is to:

Employ double insulators for road-side lines;
Employ double conductors at crossings;
Employ a continuous earthed guard wire from pole to pole;
Earth the neutral wire at one point only;
Take off service connections at the pole only;
Bond all insulator-pins where wooden arms are used;
Limit the resistance of a guard to earth, limiting the resulting leakage current to maximum of twice the leakage current;
Attach the earth wires direct to the wood pole;
Limit the loading on conductor and conductor supports to a maximum a.c. voltage of 325, for ¼-in. ice-loading;
Limit the minimum overhead clearance of conductors by giving 60,000 volts as the minimum, *i.e.* a 325-volt line must have the same minimum overhead clearance as that of a 60,000-volt line;
Limit voltage regulation for pressures up to 3000 volts to one-third that required for pressure above 3000 volts (rural district supply voltages will range between 3000 volts and 11,000 volts);
Require a subdivision of distribution mains to restrict areas liable to interruption of service;
Restricting any line from crossing a garden plot.

For distribution lines it is usually very bad policy to provide height which is just within the law and to neglect future possibilities. Such practice is likely to prove false economy, because no overhead space is left for additional conductors and wires or circuits; for distribution lines, in particular, this is bad practice, hence there is greater reason for minimum permissible overhead clearance than in the case of transmission lines. This same reasoning applies to the size (diameter) of poles, but this latter is still more important because, with ample diameter, height can be gained by pushing up existing conductors on to a pole top-fixture, or by stringing additional conductors and attaching them to a pole top-fixture —better still is it to provide ample height as well as ample strength.

For a decreased loading of ice, say from ½-in. or ¼-in. radial thickness, the height of conductors (and height and size of poles) can be made less for the same size, weight, and number of conductors; thus a less length and/or strength of pole is required for the same length of span, independent of the loading for strength calculations. For datum temperature (22° F.) and maximum loading the tension in the conductors for the same size and same metal is the same for $\frac{1}{2}$-in. and $\frac{1}{4}$-in. ice-loading, but the resultant sag is greater in the case of the $\frac{1}{2}$-in. ice-loading. At all temperatures above 22° F.,[1] the height of the unloaded conductors (for the $\frac{1}{4}$-in. ice-loading) can be less, hence a less height of pole is required than for a $\frac{1}{2}$-in ice-loading; however, the tension in the unloaded conductor for the same conditions is greater in the case of the $\frac{1}{4}$-in. ice-loading, but it is always less than the maximum allowable tension. This is interesting in showing that for the same span-length, same size, and same weight of conductor, a *less height of pole* is required for the $\frac{1}{4}$-in. loading than for the $\frac{1}{2}$-in. ice-loading, and same wind pressure in both cases; this again is further reason for recommending a less overhead clearance of conductors for the $\frac{1}{4}$-in. or $\frac{3}{16}$-in. ice-loading.

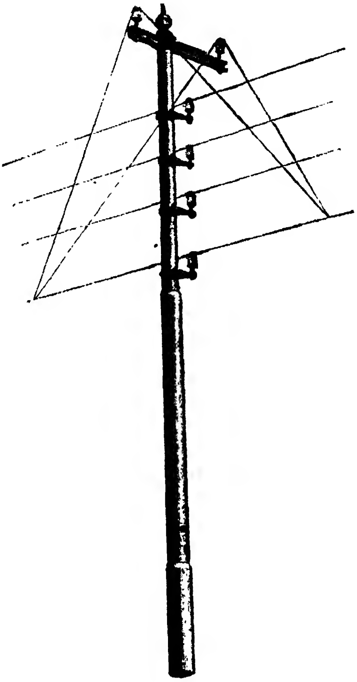

FIG. 17.—Tubular steel pole construction for distribution lines, showing the "V" guard. (*Henley.*)

Nature grows timber, from which the wooden pole is made, in such a way that it has approximately equal strength in all horizontal directions. Where wood poles are used, they should be *standard*, and should be of lengths such that when set in the ground to depths, as indicated in Table XXXII., the conductors shall have at least the minimum clearances from ground, highways, and crossings, as specified in Regulations. The minimum dimensions of the poles should not be less than shown in Tables X. and XXXIII. As regards the poles themselves, they should be:

Cut from live timber;
Free from dry rot;
Well proportioned from top to butt;
Not have curvatures greater than about 1 in. in 8 ft. 0 in.;

---

[1] Freezing point=32° F. (see p. 77).

Not have a reverse curve;
Peeled, trimmed, shaved, and roofed, etc.;
Treated by a good *insulating* preservative.

The ground-line diameter of a pole might be sufficient to give the necessary strength, but, due to the taper of the pole, the top diameter of the pole might be too small; on the other hand, some poles have so little taper that it may be necessary to apply a tape to the pole to determine which end should go into the ground—this, therefore, shows clearly a weakness in using top diameter *only* for calculating the ultimate load on a pole unless a definite minimum taper per foot of length is also specified. The taper of a pole should be known, because the greatest fibre stress of a "*new*" pole can be that point at which the pole diameter is 1·5 times the diameter where the load is taken off, and this is usually at a point above ground-line, depending on the taper of the pole. The text-matter centres on the use of wooden poles for distribution lines in general, but not exclusively.

Poles are designed to withstand the stresses calculated from the estimated maximum loads to be carried by them. Pole-strength calculations should be based on that part of a pole which decreases in strength in the quickest time. While the ground-line section of a wood pole may not be the most stressed section of the pole, it should always be so regarded because the wood almost always deteriorates most rapidly at this point, and it is at this point more than any other that sufficient strength must be provided.

Timber used for poles is strong as regards the vertical forces, but is relatively weak for horizontal forces; because of this, calculations for strength of poles are ordinarily limited to the effect of the horizontal force or side wind, and side-stays are used to very great advantage. In other words, it is the usual practice to consider only the transverse wind pressure which occurs on the line conductors and wires *plus* the wind pressure upon the line-support itself; these forces tend to break a pole by cross bending.

Before setting, all single poles or frames should be completely framed with crossarms, crossarm braces, etc. where at all possible. The poles should be set in the ground at depths given in Table XXXII.; in rock, poles may be set to a depth of 1·0 ft. less than in clay or loam. All holes should be dug large enough to admit the pole without forcing, and should have approximately the same diameter at the top as at the bottom; or, a rectangular-shaped hole, not larger than two diameters in width, can be made sloping at one end (sometimes in steps from the surface to the bottom); in this way the pole is easily slid down this angle into the ground, and it is then set in one corner of the hole so that in two directions it bears against solid ground. Poles should be set to stand vertically when the line is completed; two plumb-bobs should be used on each pole to ensure this condition—this is important for straight runs and balanced or approximately balanced arrangement of wires. Poles at line terminals, angles, and other points of abnormal stress, might with advantage be given a slight rake against the direction of the stress. After the pole is in position, only one shovel should be used in filling in the hole, while three tampers continually tamp in the earth until the hole is completely filled. When available, small rock should be used for filling, care being taken to fill all the voids with earth. After the hole is filled completely, earth should be piled up and packed firmly around the pole, or, about two feet depth of the top portion may, with advantage, form a concrete mass. Poles should be inspected after they have been subjected to a heavy rainstorm, and any fillings that have sunk should be refilled. Poles should preferably be set so that the gains (if any) in each alternate pole face each other (see also fig. 19).

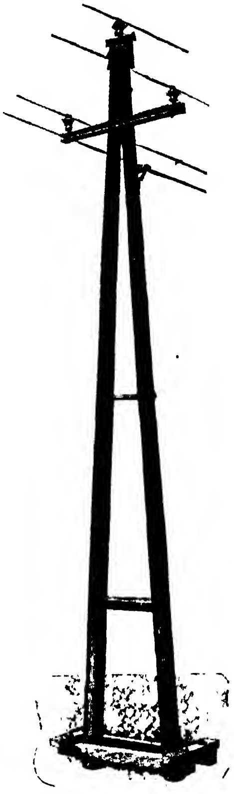

FIG. 18.—Wood "A" frame using top extension and improved base for increasing earth resistance to uplift. (*Henley.*)

To obtain the best operating conditions and a safer line, change this construction to the system, etc. proposed by the author (see fig. 6).

With respect to the choice of a support (pole, frame, or structure) for distribution lines in general, there is no question of doubt about the advantages of the wooden pole. Apart from its lower cost, the wooden pole for distribution lines always has been, and always will be, commendable because it has:

Large strength in torsion;
Equal horizontal strength in all directions;
An ideal outline to resist stresses; and
Considerable elasticity to equalise unbalanced loading and *relieve the line from ice-loading.*

In the design of a wooden pole line, which is the type more generally used throughout the world, and differs somewhat from other types, *the most* economical and most satisfactory design, construction, and operation are attained when (and only when) there is:

> Ample stability and highest insulating value of the earth surrounding and in contact with the pole, it being heavy, compact, and free from decaying effects;
>
> Ample strength and highest possible insulating value of the pole itself, set to best care for the load imposed;
>
> Ample strength and highest possible insulating value of the crossarm efficiently secured to the pole;
>
> Ample strength of pin and satisfactory insulating value, if of wood, set well up in the insulator and efficient;
>
> Ample strength of the insulator with satisfactory flash-over value best suited to the locality, durable factor of safety, and efficiently supported;
>
> Strong and efficient tie wire or clamp if used;
>
> Conductor of the metal and covering best suited to the locality, strung to moderate tension, free from brittleness and soft spots, and free from kinks or abrasions;
>
> Ample strength of stay wire (cable) of the most suitable metal, most efficiently located, set, tensioned, insulated, and guarded;
>
> Where the overhead earthed wire is used (not recommended if not properly insulated from wooden pole construction), it be of the most suitable metal, of greater strength than the strongest conductor used on the line, be of low-resistance metal, be properly tensioned, efficiently secured at each pole but *insulated therefrom*, and given the most direct path to a low-resistance earth;
>
> Relays and sectionalising equipment and apparatus installed and set so as to insure (if necessary) absolute positive action in the event of a very small leakage current-flow to earth. All these are met in the construction for fig. 6.

The function of the line support is to support the conductor and the electrical equipment at a satisfactory height above the surface of the ground. Wooden construction throughout, *i.e.* poles, crossarms, pins, and braces, offers the most economical means and best insulation per line support, and on many distribution lines (which usually have short or ordinarily moderate spans) this type of construction is the safest; the pins and braces are now more generally of metal. The weakest support part is the wooden pin, but these are made for a breaking strength up to around 1500 lbs., which is equivalent to the allowable strength of a 0·05 sq. in. copper conductor; the wooden pin is used extensively (not in this country) for voltages up to 22,000 volts.

As the insulator is designed and generally chosen with the idea of securing the maximum mechanical strength *without lowering the electrical flash-over*, this should be maintained by its supports (the pole and crossarm and/or pin) which are in electrical series, by following the same practice, and proper means should be provided to eliminate lightning danger to the pole and to give positive relay action without in any way lowering the flash-over value of the line construction, which latter cannot be considered good practice as pointed out in the text-matter and fig. 6.

Wood was, and is still, regarded as an economical material, and its insulating properties usually are, for dry climates in particular and most climates in general, considered to be of real practical value in the operation of all voltage lines, especially those designed and used for *distribution* of electrical energy. Wood construction —chiefly the single pole—was always economical, and has given satisfaction for the operation of high-voltage lines up to 220,000 volts for the "H" type, and up to 66,000 volts for the single-pole type; approximately a quarter of a century ago the author used it for the latter voltage.

It is poor engineering to provide the most effective means for causing a breakdown of insulation, and then wait for troubles to develop and cause interruptions of service by intentionally imposed strain, etc. instead of constructing for, and maintaining, every fraction of insulation and providing *proper* means for locating (if desired) all the weak spots resulting from age, atmospheric and other conditions, excess stresses, and so forth.

Treated poles should not be handled roughly, sharp tools should not be used, and the poles should never be dragged over jagged rocks; moreover, after erection, linemen should not penetrate the pole with their spurs. Poles should be protected from abrasion or penetrations which will permit moisture to enter and cause rot under the treated shell and loss of insulation, etc. Poles should be sorted, and those with standard diameter tops used on straight runs, and those with extra heavy tops used on angles or other points of excessive strain, or where additional safety is required, as at crossings. *All wood poles should be properly impregnated.*

The conductors of an overhead line are far more immune from falling and of causing danger than are the hundreds or thousands of secondary consumer's installations connected to the line; in fact, the 240-volt a.c. consumer's circuit should always be considered dangerous to life. An excellent policy would be to provide means at each line support, or at any convenient distance, so that the sub-station or station is informed of a leakage over any support or insulator—in this way faulty insulators are automatically located. A tiny apparatus on each pole, set for a given wave-length or signal, and a receiver set at the station will answer this purpose. Why burden up any pole or structure with porcelain strips and/or metal straps along wood crossarms, also a continuous earthed-wire guard earthed on every support? All these call for a higher and a stronger pole, and tend to increase interruptions and danger, as they (the latter) are vital to the most important requirement of any line or circuit, *i.e.* its insulation, and the required safety to line and linemen. To decrease bird trouble, insulating material for *metal* crossarms is necessary; but there is little excuse in the case of wood poles (for the voltages ordinarily used in distribution work) to bond the pins and/or to run a continuous earthed-wire guard from pole to pole and/or to run an earthed wire down the pole in contact with the pole, and an earthed plate *under* or at the pole into ground steeped in creosote (which is itself an insulator of some value), or in ground of *exceedingly high* resistance.

If the continuous earthed-guard wire "must be used," then in every case insulate it properly from the pole, and earth it at a distance from the pole, at frequent, selected, prepared, and/or tested points on the line and/or terminals; it will in this way serve more than one useful purpose. Insulating this earthed wire from the poles will increase greatly the insulating value of the whole line, and it will largely dispense with bird trouble and other line troubles, and decrease line costs, as an insulator is cheaper than a porcelain bird-strip, etc. Moreover, if certain selected earthing and opening points are made, many lines will be able to use this conductor as a spare power conductor in cases of emergency, etc. The continuous earthed "guard" wire would serve this purpose admirably, but it must be insulated from the pole, and other existing construction methods must be modified (see p. 15).

For wood poles, the earthing of the crossarms results in the loss of valuable insulation from the wooden pin (if used), the pole, and the helpful non-conducting properties of the earth surrounding and in contact with the pole, resulting from creosote penetrating and mixing with the surrounding earth. Conductors very rarely fall on the crossarms and, if they do, they are soon indicated at the station and/or spotted by the linemen; a conductor falling on a metal arm or on an earthed arm might be melted and fall from the pole to cause greater damage and danger, whereas the unearthed crossarm (depending on the weather conditions and the line voltage) would more likely not cause any damage or danger. If the conductor is provided with another attachment, *i.e.* double suspension, as can be expected at angles and crossings which are the most likely places for a broken wire, it would not fall from the pole, and the danger of burning or charring might then be confined to the crossarm itself in the case of unearthed arms, but for such places there are double crossarms and double insulators, hence the conductor is likely to be held in safety (see fig. 19A).

Neglecting any particular locality or place (urban or rural for the former, and crossing-span or straight-line construction for the latter), there exist many diverse conditions defining *safety*. Independent of locality or place, safety depends upon:

> Having the conductors and/or wires at a minimum height above ground such that no live part can come into contact with the highest wheeled traffic by a suitable margin—not a margin indicating lack of knowledge. The margin cannot be fixed for all voltages or all spans and sags, nor can it be fixed for all places. It is unsafe to make it too low, and it is both unsafe and costly to make it too high.
>
> A given pole is subjected to less stress when it is short and least when it is shortest, hence from this view-point it is safer.
>
> Double suspension, *i.e.* double insulators per conductor, provide a safer line.
>
> The conductor offering highest strength, highest conductivity [1] is the best and safest.
>
> Staying of the supports (poles and/or crossarms) and insulating the stay provide a safer line.
>
> Employing the best electrical system provides for a safer line.
>
> Proper protection installation and maintenance provide a safer line.
>
> Proper earthing of the neutral provides a safer line.
>
> Non-bonding of pole ironwork (hardware) provides a safer line.

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[1] This is a copper alloy conductor giving 77 per cent. conductivity and 30 per cent. greater strength for equal size of the *all*-copper. It is called by the trade name Hitenso " BB." For equal conductance it has 60 per cent. greater strength. It also has the same modulus of elasticity, same co-efficient of expansion, and same density as copper; it is a good conductor to use for *rural* lines and *long* spans.

> Employing multiple earths provides a safer line.
>
> Keeping a wood-pole line well insulated provides a safer line.[1]

Accidents and failures are, generally speaking, not minimised by having a pole or line as high as possible, and by placing so-called guards along the whole or a part of the line (see fig. 17). On the contrary, it is too often found that:

> A large number of line failures are due to conductors or other parts of the live line being burnt by "safety" devices, thus causing or starting failures;
>
> The "V" or other so-called guards provide greater danger to life and are a pest to linemen;
>
> Broken telegraph and telephone wires are very much more numerous than broken power conductors or wires connected with the system, and they are a far greater source of danger to life than power conductors, as they are principally along public highways and roads where motor traffic running at high speed can easily get entangled, and they sometimes cross above power conductors, and are strung to different factors of safety and tensions, and they rely to some extent on the belief that due to very low voltage they are safer than power conductors.

Another important matter to have in mind is that, with reference to the bonding of insulator pins, the bonding of pins has the following *dis*advantages:

> Insulators of much higher rating are necessary to give equally satisfactory performance when pins are earthed.
>
> The bonding of insulator pins results in an increase in the stresses imposed upon the insulator.
>
> Earthing of pins will permit a larger flow of current into a fault.
>
> Earthing of pins shows a great increase of stress imposed on the insulator.
>
> Relay and sectionalising methods dispense with this large current flow to insure positive action to operate relays without the earthing and bonding resorted to in this country.
>
> Operation is impaired; better operation is secured from unearthed insulator pins for all distribution voltages, whether the system is earthed or not.

---

[1] If an earth wire must be taken up a pole for any purpose, insulate it from the wood pole, from the pins, and from the crossarms.

> Chance of poor or broken bond and/or earth connections; experience has proved that trouble of burning or charring of arms or poles for low-, medium-, and high-voltage lines is practically nil where wooden crossarms and pins are not earthed or bonded.

For voltages above 3300 volts it is customary in this country to provide the top part of crossarms with an *insulating* sleeve or strip of porcelain or fibre, or some equivalent arrangement to prevent birds shorting the line; it is also the practice to do practically the opposite thing, *i.e.* provide the top or bottom part of crossarm (along its length) with a *metal* strip or strap, and attach it to the insulator pins.

Crossarms of wood should be of sound, straight-grained, selected timber, free from shakes and knots; oak, fir, and pine are best. Crossarms which have more conductors dead-ended on one side than on the other may have to be stayed from the end of the arm carrying the greater strain. The use of crossarms of steel channel-section is common in this country for all voltages; very much *wider use should be made of oak crossarms.* The advantages of wood over steel, for crossarms, are by no means of small import; they consist of:

> Reduced strain on insulators; that is to say, the metal crossarm results in poorer insulation even when non-earthed, and, if earthed, there is the danger with metal arms of burning or weakening of the wood pole at the point of its attachment.
>
> Greater safety for linemen.
>
> Decrease of bird troubles.
>
> Less disturbances and interruptions of service.
>
> Action of the wood as a resistance *in series* to earth.
>
> Reducing the chance of a power arc in case of a spill-over.
>
> For all ordinary spans, for poles and frames, experience has so far given no evidence that the mechanical strength or durability of wooden crossarms is not ample, or that they are less reliable than the pole itself. On the contrary, long and varied experience has proved that the steel arm is not so safe or satisfactory from the chief standpoint—*operation.*
>
> There should be no objection to the use of wood on any part of distribution lines for voltages up to at least 11,000.

Through bolts and gains for the required number of crossarms should be cut and bored, respectively, before the pole is set. Gains should be cut vertical to the axis of the pole, except in cases where the least ground resistance or best short-circuit path. In some parts of this country the climatic and atmospheric conditions are sufficiently severe on insulation, as we have to contend with deposits of soot, cope with salt spray, continual rains, coating of dirt or dust, etc. until insulators have to be washed, or otherwise they become semi-conductors—hence there is a greater necessity than exists in most countries for retaining all possible insulation value of the line construction. Due to the practice referred to above, which the writer cannot recommend, the theoretical factor of safety of insulators is practically wiped out; conditions are relatively worse for the lower-voltage lines, which, with wooden supports, provide for a *relatively* higher value of insulation than the higher-voltage lines, because the insulation of the line for the latter is relatively less dependent on the wooden support, which is the all-round best support for distribution lines in general.

For the higher-voltage lines (60,000 volts and above) removed from the sea coast, and where trouble from fog or soot is not experienced, the use of wood poles and structures in the place of steel poles and structures also proves, from the insulation standpoint, to have some merit—that burning can be prevented by a shunting resistance, and the shattering of pole by providing a shunt gap. For the lower voltages it is of greater importance, because advantage is taken of the insulation of the wood, which is considerable in dry climates, and is the same value independent of the line voltage. In certain localities, and for some countries, wood-pole lines with the conductors carried in a horizontal plane at the minimum permissible distance from the ground-line sometimes provide a line freer from lightning trouble without the use of the overhead earthed wire than a steel structure equipped with two of them; troubles from flash-overs, birds, climbing animals, soot, smoke, fog, salt spray, cement dust and dirt, are also reduced. The most important disadvantage is the possible leakage over weak insulators; for low- and medium-voltage lines the most important disadvantage is the possible shattering of the poles by lightning—a very remote possibility for most countries and for this country in particular, and obviated by using a shunt gap.

In the discussion of this subject, the system and line must be taken together. Underground construction cannot be compared with overhead construction, and in methods of protection and other matters, a distinction should be made. However, for *overhead distribution lines*, it should be kept in mind that there are at least four outstanding principal requirements for the best system and line, namely:

1. The best-planned line as regards *safest location from every point of view*, and one offering reasonable accessibility for inspection, etc. Wooden construction well meets this requirement.
2. The *most economical line*, consisting of standardised materials and constructed by skilled workmen under proper supervision, in accordance with reasonable standards of safety. Wooden construction certainly meets this requirement.

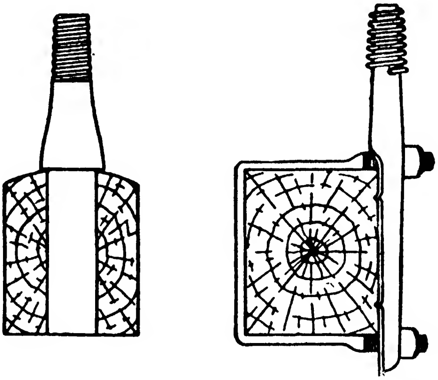

FIG. 20.—Two types of pins—one method requires part of the crossarm to be cut away to fit the pin, thus weakening the arm, while the other method actually gives strength to the wood crossarm and increases its life.

3. A line possessing the *highest insulation throughout* for a given insulator rating. Wooden construction best meets this requirement.
4. A *symmetrical polyphase system*, and line circuit of the least number of conductors for combined light and power, and over-voltage protection, offering the best all-round advantages for normal and abnormal operating conditions, and a system and line capable of supplying satisfactory polyphase service when one line phase-conductor and one phase-transformer are put out of commission. The three-phase 4-wise system and circuit best meet these requirements.

On many lines, e.h.t. lines in particular (*i.e.* voltages of 15,000 and above), pins should be of metal, and they should always extend well up into the insulator, in order to reduce the mechanical stress upon the material of the insulator, to be most effective. Where long-stalk pins are used, a broken conductor develops a very large torsional effect upon the crossarm, and an excessive bending stress upon the crossarms on corners or angles. To get the most out of an insulator, a good pin is essential, because the pin and the insulator should always work together—mechanically and electrically. Only when considered in this respect, including the full insulating value of the pole and fittings, can the maximum effective insulation and life be expected. Inadequate pin support may result in loss of much of the effectiveness gained by careful and wise insulator selection. *The whole chain of insulation should be maintained the highest, and the factor of safety retained the longest, by eliminating weak links in line design and construction.*

As a general rule, it is better to have only wooden *supports* throughout a wood-pole line when serving important loads with no duplicate or other source of supply. The problem is sometimes that of nursing weak insulators (weakened from one cause or another) in order to maintain service with a partial or weak earth on some part of the line or system; this is often a desirable feature from the view-point of the operating engineer. Relays and sectionalising devices are available, and they can be used to insure positive action *without* earthing the pins, arms, or poles. In the case of an "insulated" wood-pole line, when an insulator is broken or cracked, or lightning jumps across it, there remains the insulation of the wood to protect the line; in certain cases the wood may burn off at some point and an interruption of service may (or may not) result therefrom. In the case of earthed crossarms and earthed-insulator pins, every failure of the insulator is a low-resistance (and may be heavy) short-circuit on the line, and depending on the system used, all the harmful results that follow a short circuit of an a.c. system may happen each time a disturbance occurs on the system.

The requirements of a metal insulator-pin are that:

> It will not crack the insulator by bending or distorting within the area in the pin hole;
>
> It will be capable of withstanding a load equal to its rated strength with not over 10° bending;
>
> It will not injure the insulator by expansion;
>
> It will be quickly and easily adjusted to align the top-wire groove of the insulator with the conductor;
>
> It will be made applicable to either wood or steel crossarms;
>
> It will be clean and simple in design, have a minimum number of parts, and occupy a minimum of space within the insulator, so as to provide a large free space between the pin

and the insulator shell, and an entire absence of ridges or fins, so as to reduce arcing within the insulator.

In using the standard beam and column formulæ for computing the theoretical strength of crossarms or pins, several discrepancies are found, such as:

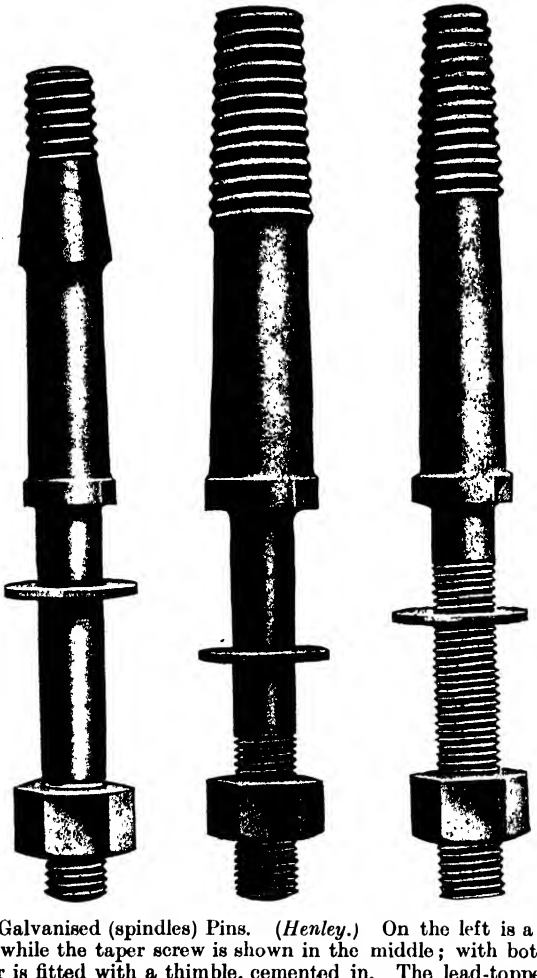

Fig. 20a.—Galvanised (spindles) Pins. (*Henley.*) On the left is a cove-seated *spindle*, while the taper screw is shown in the middle; with both these the insulator is fitted with a thimble, cemented in. The lead-topped *spindle* is shown on the right—it is screwed directly into the insulator without a thimble.

Loading is either complex or is eccentrically applied, and is extremely variable and sometimes involving a large impact loading and not direct, which is the assumption of the beam and column formulæ.

The combined action of steel and wood is usually different from that of any one material alone.

The materials are not strictly rigid as assumed in formulæ.

The materials are rarely true to the shape assumed in formulæ.

The threads of pins, of bolts, stay-rods, and so forth are subjected to rust, and it is often difficult to take off nuts; to avoid this trouble they can be thickly coated by brushing or wiping over them a solution compound of tallow, tar, and pitch.

Where the construction is of wood crossarms, non-earthed insulator-pins, and a wood pole free from earthed wires (which practice permits of the highest possible flash-over voltage), faulty insulator and the respective location can be automatically indicated to the operator at the station, or to the lineman (at his section-house or any other receiving point), or they can be detected by means of a head-set of wireless-telephone receivers with *portable* aerial; this also is of much practical importance for stay-wire installations, which are the more likely points for leakage current, as they represent strain and excess stress positions.

Bonding may *in rare cases* be necessary where a line is located on the sea coast, or where dust is blown from cement works or steel mills. For rural distribution lines in general, pin-insulator connections should not be bonded unless or until there is sufficient evidence (due to inferior insulators, or a too high voltage on primaries, or/and to very bad atmosphere, etc.) of charring. For voltages up to about 22,000, experience has proved that bonding of insulator-pins is quite undesirable.

For single-circuit lines of copper up to 0·10 sq. in., single poles for spans up to about 250 ft. can usually be used; and for double-circuit lines of copper up to 0·15 sq. in., "A" frames are economical up to about 400 ft. spans, according to the foundation, respectively. For wood-pole construction the limit of span-length is very rarely determined by the mechanical strength of the conductor. For moderate spans, wooden poles usually prove more economical in first cost, and for this country, need less maintenance than steel frames of structures, which are highly corrosive in this atmosphere if not effectively galvanised. The higher voltages have been one of the chief causes for increasing the length of span, the purpose being to reduce the number and consequent costs and hazards of the extra-high voltage insulators to a minimum.

The most economical span-length should be longer the higher the voltage, the larger the conductor, and the greater the number of conductors per support. For a given span-length, the cost of a support will be greater the higher the voltage, the larger the conductor, and the greater the number of conductors supported per support. It is not the theoretically most economical span-length the operating engineer requires, of far greater economic importance is continuity of service as well as high-service standards during the life of the line, which latter must also be considered in terms of the longest period of years.

Span-length is increased by taking the very best advantage of the profile of the country crossed, and by keeping as close as possible to the allowable minimum height prescribed by law. Several methods are available for reducing or keeping a line to the allowable minimum ; some of these are:

Decrease the line voltage.
Provide a flat arrangement of conductors.
Provide a minimum possible separation of conductors.
Decrease the span-length.
Employ a higher strength conductor.
Decrease the size of conductor but maintain the strength.
Decrease the weight of conductor.
Make the best advantage of the profile.
Employ a conductor metal in which the variation in sag, with changes in temperature and load, is smallest.
Use pin-type insulator construction.
Dispense with the earthed-wire guard or use it as part of the circuit.
Have the present-day minimum height value (in Regulations) relaxed.

Some of these cancel out others, and for best practice some are outweighed by other more important advantages and requirements.

For every case there is one particular span which is the most economical and practical. In flat country, designs are mainly based on strength in the transverse direction of the line, except at as few points in the line as possible; hence, wind pressure is of the greatest importance, *i.e.* the kind of metal to use for conductor is of greatest importance (see p. 71), and *copper* has the advantage.

The economic line cost will increase with the line voltage, but the economic span-length will decrease with the decrease in voltage for the same size and kind of conductor material. For high-strength *insulators* the more correct economic span will be longer.

REPORT ON THE CONSTRUCTION OF LINE.

(CONSTRUCTION PROGRESS.)

Location.	Rights.*	Station Elevation.†	Support No.	Drawing Design No.‡	Type of Support.§	Location approved.	Excavation.	Footings.	Material delivered.	Erected Supports.	Insulators and Crossarms erected.	Wires and Conductors erected.
						Progress is marked on this portion. Each column is marked in dot-dash line or in different colours (giving date of each change until completed). In this way both periodic and total progress can be seen.						

Remarks ....

....

....

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* Wayleave, ownership, or agreement.

† Take from Survey Book.

‡ Reference to drawings, giving details of design, stresses, specification, etc.

§ Single pole, "A," "H," or other frame or structure.

Pole depths depend on the length of pole and whether they are on a straight run or at an angle; in earth they are usually made to a depth of *one-seventh* of the length of pole for poles up to 50 ft. in length. Wood-pole setting also depends on the kind of ground, and several methods are available, namely:

> *In rock;* set poles to a depth from 1 ft. 0 in. to 1 ft. 6 in. less than in good sound earth (see Table XXXII.).
>
> *In soft earth;* so soft that poles cannot be made stable by bracing or staying, set them in bog-shoes.
>
> *In concrete;* where exceptional stability is required for a pole setting, place the pole in concrete. The concrete filling should extend at least 1 ft. 0 in. from the pole on all sides and be carried about 6 in. above the ground level and bevelled to shed water; the mixture in general should consist of one part of cement, 2·5 parts sand, and 5 parts broken stone or clean large gravel. The pole should be solidly braced in position and the bracing left until the concrete is hard.

TABLE XXXII.

PRACTICAL SETTING OF WOOD POLES IN GOOD SOUND EARTH.

Length Overall in Feet.	*Stout Poles.*		*Depth in Ground* in Feet.	
	(Butt) Inches Diameter.	(Top) Inches Diameter.	*Straight* Lines.	*Curves* : Corners and Extra Strain Points.
30	10¾	7½–8½	5½	6
35	11¼	7½–8½	5½	6
40	12	7½–8½	6	6½
45	13–13½	7¾–9	6½	7
50	14	7¾–9	6½	7
55	14½	7¾–9½	7	7½
60	15½	8–9½	7	7½
65	15½–16¼	8–9½	7½	8
70	16–17	8–9½	7½	8

A common method of computing the strength of an anchor is to figure the weight of a cone of earth with its apex at the anchor, base at the ground surface, and sides at the characteristic angle of surface of the soil. Actually, this action takes place only near the surface of the ground, and at the depth at which anchors are usually buried, the strength depends rather on the area of the anchor and the resistance of the ground itself to compression.

The strength of wooden poles or frames set in concrete, or where the base is otherwise rigidly held, may be taken as approximately double that for ordinary setting in earth for equal depth of setting. Where frames or structures are used, the setting is of extreme importance. In this country it is usually stated that the wooden "A" frame is 4·5 times as strong as a single pole of the same diameter as those forming the frame. In considering this or any other relative strength value, it is necessary to have in mind that the strength of such frames will not be realised unless that portion of each leg in the ground is prevented from moving relatively to the other, and ordinary setting is never likely to effect this, so that much stronger trussing of the poles must be adopted and/or the frame must be set in concrete, which is the best solution when considered in added life, increased strength, and increased factor of safety, etc. The strength of the "A" wooden frame is a little better in practice than the "H" frame, but this latter type has many advantages. The "H" frame lends itself to more convenient arrangement of conductors, and the cost of bracing is offset by a saving in height for the same length of pole as compared with the "A" frame. With both types, the frame will generally up-root before breaking, hence the foundation is the principal deciding factor and not the frame. Two poles properly braced together are stronger than the same poles spaced in A or H or any other form. Provided the foundation of an "A" or "H" 2-pole frame has ample resisting strength to uplift, it is no stronger than 1·67*d* of the single pole, where *d* is the diameter of single pole. In other words, for equal strength, the single pole must have 67 per cent. greater diameter than the poles[1] of the "A" frame, which gives *support* diameter ratio of 2 : 1·67 in favour of the single pole, with less ground space and less surface exposed to rot, etc.

To arrest ground-line pole decay, and at the same time provide a perfectly solid filling between the pole and the upper part of the excavation, the top few feet of the hole should preferably be filled in with well-tamped concrete, finished at the top with the surface raised above the ground and sloping away from the pole, forming an effectual watershed.

Where wood crossarms are used, one or two thicknesses only are carried in stock; the minimum sizes vary with the crossarm length and number of conductors carried, that is, the length of level arm and the possible stress due to both vertical and longi-

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[1] In practice, the *strength* of the "A" frame is often that of the two poles only.

tudinal loads vary with these factors. The ordinary oak crossarm will withstand, with a good margin of safety, the total vertical load of all ordinary conductors under the assumed maximum loading conditions up to spans greater than that which a single pole is ordinarily subjected to; furthermore, it is as durable as the wood pole itself. For crossings, corners, and for heavy loads, larger or double crossarms are always advisable. The conductors may, at some one temperature and loading of wind and/or ice exert balanced forces on the crossarms in tangent sections of pole lines. At other temperatures and loadings the forces may be to some extent unbalanced, but the longitudinal unbalancing will not be severe except at angles and dead ends, unless and until a conductor should fail. The transverse wind load may break fastenings of the conductors and crossarms, but the vertical load is usually the most serious for crossarms. Double crossarms properly blocked should be used at crossings, at unbalanced corners, at dead ends, and on long spans, as an extra precaution to provide additional strength as well as additional conductor fastenings. Double-crossarm construction prevents the crossarm from tilting after being under continual strain for long periods of time, which might cause certain pins to pull out. There is no necessity for using the double-crossarm, and little or no excuse for using—with medium or small-sized conductors—double insulator *short span* or ordinary span construction *alongside* of roads, as required in this country. At strain positions, crossarms should be fixed so that pull draws the arm to the pole and not from the pole.

Where crossarms are used, the use of spreaders permits a number of services to be taken from one or both sides of a pole with equal clearances from the line conductors, and is of special value where joint occupancy of poles is in practice (see also fig. 44). Service connections and branches can be tapped off mains by the aid of these spreaders (or spreader-brackets), making use of crossarms already installed and in use. By using spreaders, arranged to fasten to the crossarms by means of clamps, the danger of the arms becoming detached is avoided.

For primary and secondary line construction there is the choice of using vertical or horizontal arrangement of conductors; the choice may be somewhat aggravated in crossarm *versus* rack secondary construction for secondary mains. Some of the advantages for the horizontal arrangement of conductors or wires are as follows:

Less height of pole for same number and same size of conductors;

Less total wind on conductors;

Less size of pole for same number and same size of conductors;

Much superior insulation where wooden non-earthed construction is used;

Less chance of short circuit of all circuits with one broken conductor; or earth, with loose or slipping tie wire;

More accessible for single- or double-circuit arrangements;

More capable of easy duplication of circuits;

Better balance of load, where only one side of *vertical* rack or other arrangement is used;

Much less danger from bird trouble and earths at the pole;

Less chance of short circuit due to ice falling from conductors unevenly, or due to number of birds on conductor in centre of span;

Pole top bracket can be used much higher than top of pole;

As the number of service wires for most rural lines will be four at the most (two single-phase, or one three-phase 4-wire, circuits), the horizontal arrangement using one crossarm will permit cheaper and safer line construction.

As regards the vertical rack arrangement of conductors, some of the advantages over the horizontal arrangement are:

Possibly less total snow on all conductors;

Possible advantage in the crossing of conductors when making taps;

Possible closer spacing of the phase-conductors by the vertical arrangement (see also fig. 10, right-hand side).

When only a lighting circuit branch of one or two wires is taken from a pole, the tap is often made by the use of spreader-brackets which are fastened to the crossarms. All taps and connecting wires passing from one level to another for vertical or horizontal arrangement of the conductors on a pole should (as far as possible) be perpendicular, and all taps, branch wires, and loops crossing from one side of the pole to the other side should cross horizontally, *i.e.* be carried across the pole to the end of the crossarm, then continued from the crossarm to the consumer's service connection in as direct a line as possible, making the run, as nearly as practicable, in a horizontal direction; they should preferably be made on one side of the pole only, *i.e.* the crossarm side, in order to keep the other side of the pole free for climbing, making repairs, etc.

In this country, it is specified that service lines shall be connected to line conductors at a point of support *only*, and shall be fixed to insulators on consumer's premises, and that every part of a service line (other than a neutral conductor connected with earth), which is accessible from a building with the use of a ladder and so forth, shall be efficiently protected by insulating material or by other means. For the most successful operation of any line, the important requirement is *insulation*, and the general tendency is to increase the spans. In this country span-lengths are limited by law, and one of the most important limits for secondary lines is that of making taps at the pole *only*, also taking off service taps at a certain permissible angle. With proper line construction, service taps may be taken off anywhere; in this way we may obtain at least five advantages providing safety and greater economy in construction, namely:

> A better insulated line, as no earthed or rigid support is used—insulated spacers are used;
>
> Use of much longer span construction than is possible with present methods and restrictions;
>
> Greater safety is more likely to be provided against a broken wire falling and becoming a danger, because it can often be held up owing to having direct or/and the straightest possible service runs from side to side of a street, which leaves little or no surplus suspended wire to sag as would be the case in most cases when taken from the pole direct to consumer's service connection;
>
> A cheaper secondary line distribution;
>
> Neater appearance, as all residential lighting service connections are taken direct.

All taps and connecting wires running from one level to another, and from one side of the pole to another, should be made in vertical and horizontal runs, and in such a manner as to maintain at all times the clearances required for safe and good practice. All bends should be made neatly at right angles, and free from kinks; the radius of the bends should not be less than 1 in. For 0·05 sq. in. and smaller conductors, taps may be made by taking not less than three complete turns (long wraps) of the tap about the conductor; cleaned thoroughly, and soldered. For larger conductors the tap may be made by wrapping the tap tightly to the conductor with soft-drawn 0·0025 sq. in. wrapping wire.

For the higher voltage lines and larger-sized conductors, the conductor should rest on top of the insulator, and a proper top-tie made. The conductor should be attached to the top of the insulator on a straight run of line. At angles or corners the conductor should be attached to the side of the insulator, and always on that side where the strain will come on the insulator and not on the tie-wire. For lower voltages and smaller sizes of conductor, the side tie is satisfactory. On straight runs, and where conductors are placed on the side of insulators, conductors on pole-pins (where used) should be attached on the side of the insulators foremost from the pole; other conductors (on the crossarm) should preferably be on the side of the insulator nearer the pole. All ties, insulated or bare, should be made with wire and/or insulation of the same material as the line conductor, and should be soft-drawn; no tie-wire should be used a second time. Clamps may be used, but they are more expensive and not so flexible.

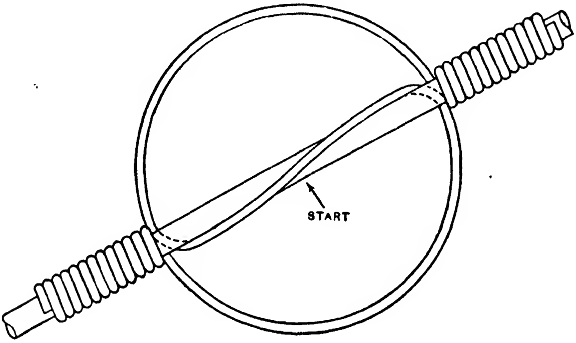


FIG. 21.—A top wire-tie which combines security and economy.

If a line conductor is allowed to be free in the groove on the top of an insulator there is a tendency, should the conductor elongate from any cause, for the whole of the sag to be concentrated at one point. For instance, it is rare that two poles are at exactly the same level, and often the conductors are run "up-hill," in which case, if they are not tightly held in the insulators, the span at the foot of the slope (or at the lowest level) may get more than its share of the sag—perhaps far too much. Ordinary tie-binding is not, as a general rule, capable of withstanding a greater longitudinal pull than about 25 per cent. of the breaking strength of the conductor it is holding. It is not exaggerating to say that one of the most skimped parts of a line is that of the tying down of the line conductor to the insulators. See clamp arrangement in fig. 22.

Where possible, make joints at the pole where the conductor can be so arranged as to relieve the joint from strain. Splices should be made so as to be secure mechanically and electrically before solder is applied. For *solid*, medium, and hard-drawn copper (conductor of 0·05 sq. in. and smaller) the two ends to be spliced should be scraped perfectly clean and free from insulation (if insulated) for the necessary length, and each should be given one complete wrap followed by at least four complete close-up wraps about each other. The ends of the wrap should then be cut close to the conductor, and the entire joint well soldered.

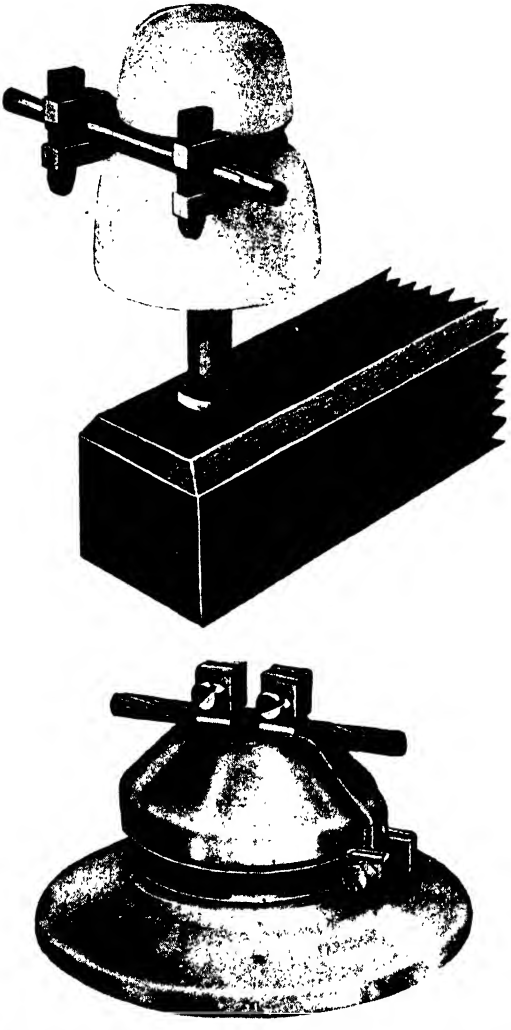
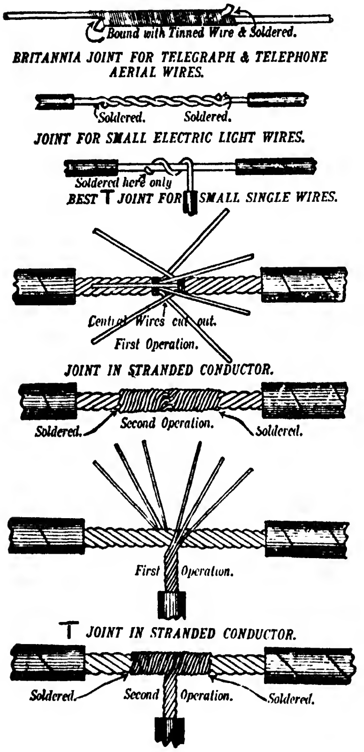


FIG. 22.—Showing practice of crossarm and pin and type of holder (clip and clamp) in place of a tie (binding) wire. (*Henley.*)

Solder should be used on medium hard-drawn wire in such a way that it will not anneal the wire, and the solder burrs should be wiped off and the entire joint covered with friction tape to the same thickness as the insulation (if any) of the line wire. For *stranded* conductor, the end to be spliced should be scraped perfectly clean and free from insulation for the necessary length, and then unstranded; the wires should be spread, pulled straight, and thoroughly scraped and cleaned. The wires of the strand should then be interlaced or dovetailed and pulled out so that they lie closely along the cable; and then the wires be served individually at least six times around the cable and cut off close to it. The whole joint should be thoroughly soldered and taped to the same thickness as the insulation of the cable. Other approved (wrapped or spliced) joints may be used as desired (see fig. 22*a*), or splicing sleeves may be used. Some sleeves have soft interiors and hard exteriors, so that the hard-drawn copper conductor embeds itself in the soft interior of the sleeve, making contact and a good mechanical joint.

The kind of joint depends on the size and kind of conductor (wire or cable), and whether soft or hard-drawn. The sleeve joint is a good one. Where used it will sometimes be found convenient to tape the end turns of large sleeve-splicers so that the tip of conductor will not catch on the crossarm when stringing-in. For copper conductor of the more common sizes, much use is made of seamless splicing sleeves for all *bare*, medium, hard-drawn metal, and, for medium hard-drawn *weatherproof* of larger sizes, the splicing sleeve (or the three-wire splice) is sometimes used. On splicing stranded conductors the wrench used for twisting should be turned in the direction so that after splicing is completed the twist in the sleeve is in the opposite direction to the lay of the cable (strand). A good splice for annealed and soft-drawn copper is to make at least five full turns with four turns of the wire at each end of the splice, soldering two of three turns in the centre part of splice. Always scrape ends clean and free from insulation, and use fine sandpaper to remove all traces of grease, particularly in sleeve splices. Solder all splices preferably *with ladle*, and after soldering clean off all burrs carefully. Use tape on splices on medium hard-drawn bare conductor in sea-coast districts; tape weatherproof conductor splices with two layers of tape and apply the tape while splice is still warm (see fig. 22*a*).

The top of each pole may be roofed one way or both ways (as desired) at an angle of 45°. The poles may be painted to improve their appearance only, green paint is a good colour as it tones with the countryside. Life of a newly creosoted pole is increased by tarring it below ground. Poles that are to be painted and/or tarred should be given a primary coat before being taken from the yard. After the pole is set, and construction work thereon has been completed, the poles already painted may be given a second or finishing coat of paint. All pole fixtures can be painted when this finishing coat is applied. Each pole should be numbered and the number should be attached either by a suitable metal plate, painted on, burnt on, or stencilled on the pole. Where poles have been recently creosoted, painting the surface is of very little value as it will not take and retain.



BRITANNIA JOINT FOR TELEGRAPH & TELEPHONE AERIAL WIRES.

JOINT FOR SMALL ELECTRIC LIGHT WIRES.

BEST T JOINT FOR SMALL SINGLE WIRES.

JOINT IN STRANDED CONDUCTOR.

T JOINT IN STRANDED CONDUCTOR.

Fig. 22a.

All line hardware should be galvanised to hot dipping galvanisating specifications. All lag screws should be driven in only to the length of the thread but no further, and they should then be set to place with a wrench. Bolt-threads should not be burred (see p. 151).

When a pole has depreciated owing to rot it must be replaced or reinforced if it is required to maintain a definite standard of construction. Wood poles are usually installed so that they have a certain factor of safety when new, *i.e.* at the time they are put into the ground; then, when rot has penetrated so amply as to leave only the minimum working strength (minimum permissible diameter of firm wood), they should be removed or reinforced. Too often wood poles are renewed or removed after they have caused damage or an interruption of service; in all cases they should be removed or renewed whenever the surplus available strength falls below a certain specified amount, which should be at least that strength necessary to carry the estimated or assumed safe total load on them.

Sometimes treated poles decay very rapidly, but this is more often caused by the opening up of seasoning cracks, exposing the untreated wood to fungi attack. Pole tops should be covered with a coat of preservative to close the grain, which is porous, and/or a galvanised roof can be fitted as a protection from sun and rain. Painting a wood pole closes up the pores and helps to retain its insulating properties, but if the pole is already soaked with moisture, painting is likely to assist in its decay. Successful pole preservation requires a good sound pole to start with; a decayed pole cannot be made strong by any kind of treatment with preservative.

It is often found that poles dry up during summer, and new cracks form and the older ones widen. This may give the fungi a chance to attack the wood in spite of the preservative applied to the pole. To provide against this, the poles should first be charred. Charring a pole is a very good way of making it more durable (just the opposite to painting it when already saturated with moisture); this is due to the fact that charcoal inhibits dry rot. However, new cracks are formed at the charring, and the existing ones are opened up to the greatest possible extent, which is the required condition; this is a desirable feature of charring, as it allows impregnation all the way down. Also, this treatment of the wood has opened the cracks so wide that the warmth of the sun in summer will not open them any wider. And charcoal being a porous substance absorbs even more of the creosote than the wood can do, and this excess quantity is later given off to the wood.

Fig. 23.—Showing type of stay-wire insulator. (*Henley.*)

Tarring a pole after it is saturated with moisture is of very doubtful value because, to start with, no one can be certain of the amount of moisture and quality or depth of penetration of creosote into the wood. The tar merely covers up the surface cracks. And for an unpainted pole, when water enters the cracks above the ground-line it is prevented by the tar from leaving, and the tarred pole is therefore more quickly destroyed than one not treated with tar; in fact, the tarring serves to give the fungi increased facilities for attacking the wood, and therefore painting and tarring a used or untreated pole go together.

When the mechanical loads to be imposed upon the pole are greater than can be safely supported by the pole, additional strength is provided by the use of stays or stubs and struts—preferably stays. This applies particularly to angles and terminals where the conductor stresses are sufficiently unbalanced to make staying necessary. Porcelain strain-insulators of the interlocking type should be used preferably on *all* stay cables (commonly called wires) attached to poles or to stubs or struts; the strain insulators should be not less than 6 or 7 ft. nor more than about 9 ft. from the pole or stub. When staying from a pole—to a pole or stub—strain insulators should be used at both ends; of course there are exceptions. When staying from a pole or stub to an earthed anchor, only the pole or stub end should have the strain insulator. When no conductors (or wires) are attached to the stub other than a stay, and an earthed anchor is used, no insulators need be used in the stay on either side of the stub. Where two stay cables are used, they should be on the same collar or be metallically bonded. The strain insulator should not be less than 9 or 10 ft. from the ground-line when in a vertical position.

TABLE XXXIII.

STANDARD SIZES OF FIR POLES.

	Light.			Medium.			Stout.		
Length.	Diameter at Top.		Minimum Diameter at 5 Ft. from Butt End.	Diameter at Top.		Minimum Diameter at 5 Ft. from Butt End.	Diameter at Top.		Minimum Diameter at 5 Ft. from Butt End.
	Minimum.	Maximum.		Minimum.	Maximum.		Minimum.	Maximum.	
(Ft.).	(In.).	(In.).	(In.).	(In.).	(In.).	(In.).	(In.).	(In.).	(In.).
18	5	5¾	6	..	..	..	..	..	..
20	5	5¾	6	..	..	..	..	..	..
22	5	5¾	6¼	..	..	..	..	..	..
24	5	5¾	6½	5½	6¾	8	..	..	..
26	5	6	6¾	5¾	7	8¼	7½	9	10¼
28	5	6	7	5¾	7	8½	7½	9½	10½
30	5	6	7¼	6	7¼	8¾	7½	9½	10¾
32	5	6¼	7¼	6	7¼	9	7½	9¾	11
34	5	6¼	7½	6	7½	9¼	7½	9¾	11¼
36	5	6½	7¾	6	7½	9½	7½	9¾	11½
40	5	6½	8	6	7½	9¾	7½	9¾	12
45	5¼	6¾	8¾	6½	8	10¾	7¾	10	13
50	5¼	7	9½	6½	8¼	11½	7¾	10¼	13¾
55	..	..	..	7	8¾	12½	8	10½	14¾
60	..	..	..	7	8¾	13¼	8	10½	15½
65	..	..	..	7	9	14	8	10½	16¼
70	..	..	..	7	9¼	14¾	8	10½	17
75	..	..	..	7	9½	15½	8	10½	17¾
80	..	..	..	7	9½	16¼	8	10½	18¾
85	..	..	..	7	9¾	17½	8	10½	20

Table XXXIV.

Breaking Strengths of Galvanised Steel (Stay) Wires and Cables.

No. of Wires.	Weight in Lb. per 1000 Yd.	Approximate Breaking Load (Lb.).		
		25 Tons per Sq. In.	45 Tons per Sq. In.	60 Tons per Sq. In.
4 S.W.G. single wire .	423	2,670	4,800	6,400
5 ,, ,, ,, .	363	1,970	3,560	4,750
6 ,, ,, ,, .	292	1,620	2,915	3,890
7 ,, ,, ,, .	246	1,360	2,450	3,260
8 ,, ,, ,, .	206	1,125	2,020	2,700
9 ,, ,, ,, .	167	910	1,640	2,180
10 ,, ,, ,, .	133	720	1,290	1,720
7/8 S.W.G. strand .	1,540	7,400	13,300	17,800
7/9 ,, ,, .	1,230	6,000	10,700	14,400
7/10 ,, ,, .	980	4,740	8,520	11,360
7/11 ,, ,, .	810	3,890	7,000	9,330
7/12 ,, ,, .	655	3,130	5,630	7,510
7/13 ,, ,, .	515	2,440	4,410	5,870
7/14 ,, ,, .	360	1,885	3,340	4,450
7/15 ,, ,, .	290	1,500	2,710	3,610
7/16 ,, ,, .	240	1,185	2,130	2,840
7/17 ,, ,, .	180	910	1,640	2,180
7/18 ,, ,, .	130	660	1,200	1,600

Stay cables attached to anchors should be covered with a suitable guard if they are in a position where there is a possibility of a person touching them. Care should be taken to see that the size of the anchor-rod is above ground, so that the stay cable will not be in contact with the earth. As a general rule, no insulator is required in a stay cable attached to *thoroughly earthed* steel (pole, frame, or structure) construction. Stay anchors should be located a distance from the foot of the pole and be not less than approximately one-fourth of the height from the ground to the point at which the stay is attached to the pole. A second log of wood should be used and be buried in the ground to a depth depending on the amount of strain to be carried and the character of the ground. The length of the log should be at right angles to the direction of the stay. Anchor holes should be back-filled in the same manner as holes for the poles.

All poles should be fitted with a collar, or be bound with a galvanised tin plate, before the stay cable is attached (see fig. 24), and galvanised stay-clamps should be used at the pole and anchor ends. In new construction work, and rebuilding old lines, stay cables should be placed and pulled to the required tension before

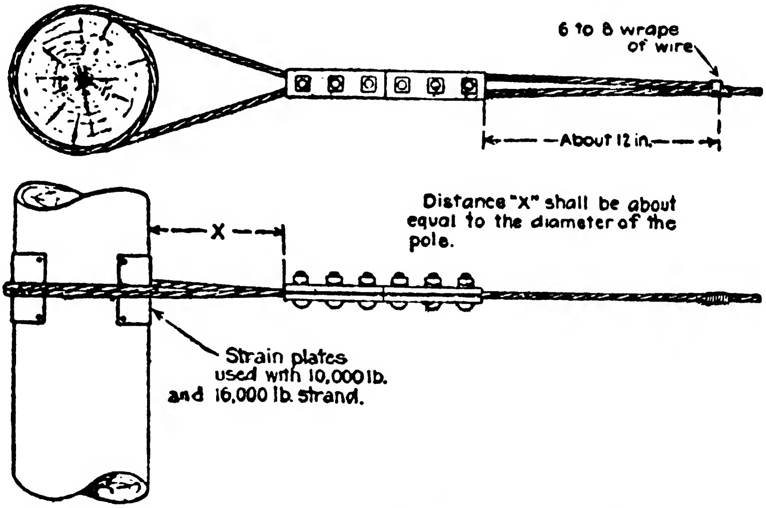


FIG. 24.—Method of attaching stay-wires to wood poles.

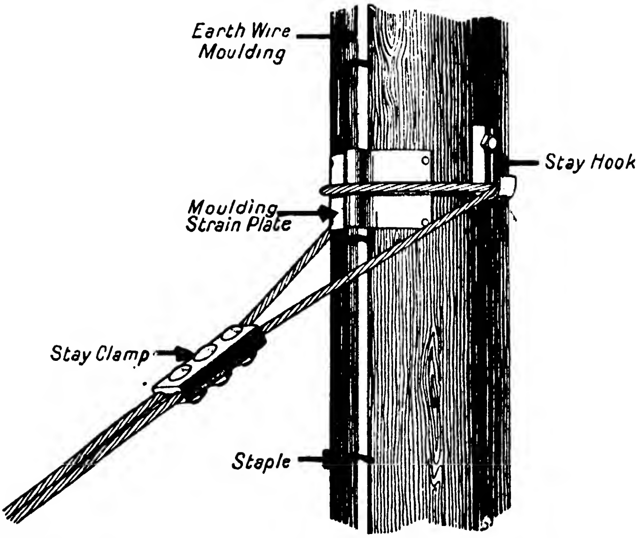


FIG. 25.—Showing method of holding and clamping stay-wire on wood poles with earth-wire leading down from the crossarms. (*Note.*—The clamp has a groove on each side for giving maximum clamping surface.)

the conductors and/or wires are strung. After the conductors are pulled up to their final position, the stays should be carefully inspected to see that they are holding the poles in a proper manner;

if they are not carrying the full strain, they should be pulled up until they are in tension and proper position.

Stays should be attached to poles in such a manner that they interfere as little as possible with the linemen climbing or working thereon. When two stays are required on the same side of single- or double-poles or frames, both stays should be attached to a single anchor, unless the ground conditions are such that one anchor will not hold the pull thus put upon it. When two stays run to a pole or stub, the attachment of one should be entirely independent of the other. The anchor for head and back stays on multi-pole *frames* ("A" and "H" frames), at locations other than angle positions, should be located approximately midway between the two legs, in line with the conductors and at the proper distance from the base of the frame, to secure the proper angle between the stay and the frame; this is simple for "A" frames. And where it is known that poles are (or a section of a line is) unduly exposed to heavy winds, stays should be placed on such poles or sections. See p. 93 for stay calculations.

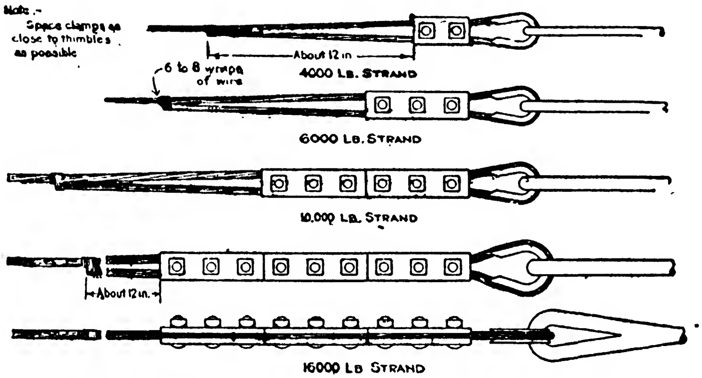


FIG. 26.—Methods of attaching stay-wires to the stay-rods.

Where it is impossible or impracticable to locate single poles, and where the wayleave situation is objectionable, or such that the anchor locations for side-stays would not be allowed or be costly, braced frames or a steel-latticed pole may be used, or wood frame with head and back-stay may be used in place of single poles. Terminal poles or frames should be head-stayed against the strain of the line. On ordinary construction, when the sum of two adjacent spans at any pole is greater than three times the standard or normal span-spacing, the pole may with advantage be head-stayed each way; poles on steep hills are sometimes head-stayed to take the down-hill strain of the line. Poles located at high points in the line, where the elevation drops rapidly in either direction for a considerable distance, are also often head- and side-stayed in both directions.

We thus see that wherever the conductors tend to pull a pole or crossarm out of place, stays are used. When installed, they should take up all of the strain so that the pole will, as much as possible, act merely as a strut. The only exception to this is in the case of angles up to about 10°, when poles which carry only a few smaller-sized conductors (up to, say, six of 0·02 sq. in. copper) may be given a slight rake and ordinary straight line construction used. Where the ground is not firm, or where the strain is greater than this number and size of conductors, angle poles should be stayed. The sizes of high-strength steel cables to use for the different conditions and *number and sizes of copper conductor* are given in the following table:

TABLE XXXV.

SIZES OF STAY CABLE TO USE.

Number of Conductors and Size in Square Inch.		Range of Angle.						Terminal or Dead End.	
		0° to 10°.		10° to 30°.		30° to 60°.			
		Required Size and Number of Stays.							
Size.	No.	No.	Size.	No.	Size.	No.	Size.	No.	Size.
0·02	2	..	..	1	$\frac{5}{16}$	1	$\frac{5}{16}$	1	$\frac{5}{16}$
	3	..	..	1	$\frac{5}{16}$	1	$\frac{5}{16}$	1	$\frac{5}{16}$
	4	..	..	1	$\frac{5}{16}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	5	..	..	1	$\frac{5}{16}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	6	..	..	1	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
0·025	2	1	$\frac{5}{16}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	3	1	$\frac{5}{16}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	4	1	$\frac{5}{16}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
0·05	2	1	$\frac{5}{16}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	3	1	$\frac{5}{16}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$	1	$\frac{1}{2}$
	4	1	$\frac{5}{16}$	1	$\frac{1}{2}$	2	$\frac{1}{2}$	1	$\frac{1}{2}$
0·075	2	1	$\frac{5}{16}$	1	$\frac{1}{2}$	2	$\frac{1}{2}$	1	$\frac{1}{2}$
	3	1	$\frac{5}{16}$	1	$\frac{1}{2}$	2	$\frac{1}{2}$	1	$\frac{1}{2}$
	4	1	$\frac{5}{16}$	1	$\frac{1}{2}$	2	$\frac{1}{2}$	2	$\frac{1}{2}$
0·15	2	1	$\frac{5}{16}$	1	$\frac{1}{2}$	2	$\frac{1}{2}$	2	$\frac{1}{2}$
	3	1	$\frac{5}{16}$	1	$\frac{1}{2}$	2	$\frac{1}{2}$	2	$\frac{1}{2}$
	4	1	$\frac{5}{16}$	1	$\frac{1}{2}$	2	$\frac{1}{2}$	2	$\frac{1}{2}$

Note.—See Table XXVI. for galvanised steel, stranded, high-strength cable.

When a stay cannot be carried directly to the ground and there are no other poles or permanent structures to which it may be attached, a stay stub may be used. Stubs should be of sufficient length to ensure stays clearing footways and roadways by not less than the regulation height; they should be stayed in the same manner as line poles.

Although stays are necessary for places where conductor stresses are not balanced, they are also valuable to prevent undue increase of sags in adjacent spans.

When stringing conductors and/or wires, the reels should be firmly mounted on portable stands and secured against possible displacement. The reel should be equipped with a suitable breaking device to keep the conductor always under some tension. Particular care should be taken at all times to prevent the conductor becoming kinked or abrased or twisted in any manner, and should this occur, it is imperative that the damaged part of the conductor be cut out. For the stringing and sagging of the conductors, snatch-blocks should be suspended from each crossarm or insulator support in such a position that the conductor, in passing over the sheave of the snatch-block, will be at approximately the elevation at which it will be finally held by the conductor clamp. The snatch-block should preferably have hardwood sheaves of large diameter and wooden frames, and should be so designed and finished as to reduce friction to a minimum and prevent injury in any way to the conductor as it passes through.

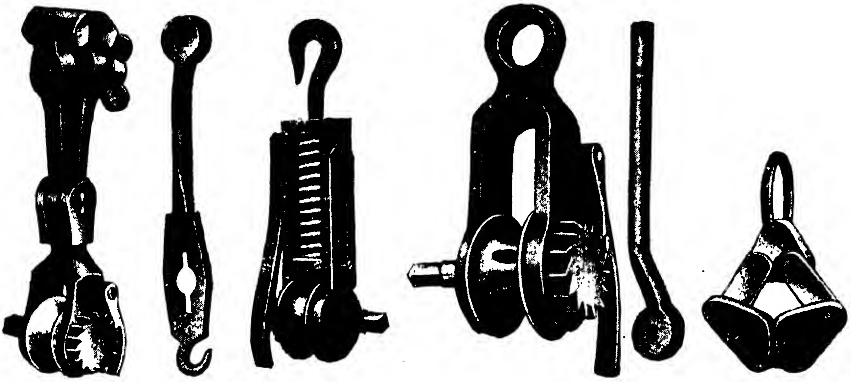


Fig. 27.—Lineman's ratchet and draw-tongs (or come-along) for stringing conductors. (*Henley.*)

In sagging the conductors, the dynamometer is more generally used to obtain the correct tension. The conductors should be pulled up to and held for a few minutes at a tension somewhat higher than normal, and then be slacked off to normal tension. The conductors may (if desired) be sagged by sighting. In sighting, it is desirable to choose a span where the length is about normal and the poles of which are practically at the same elevation. The horizontal span-length is first measured correctly, and from a

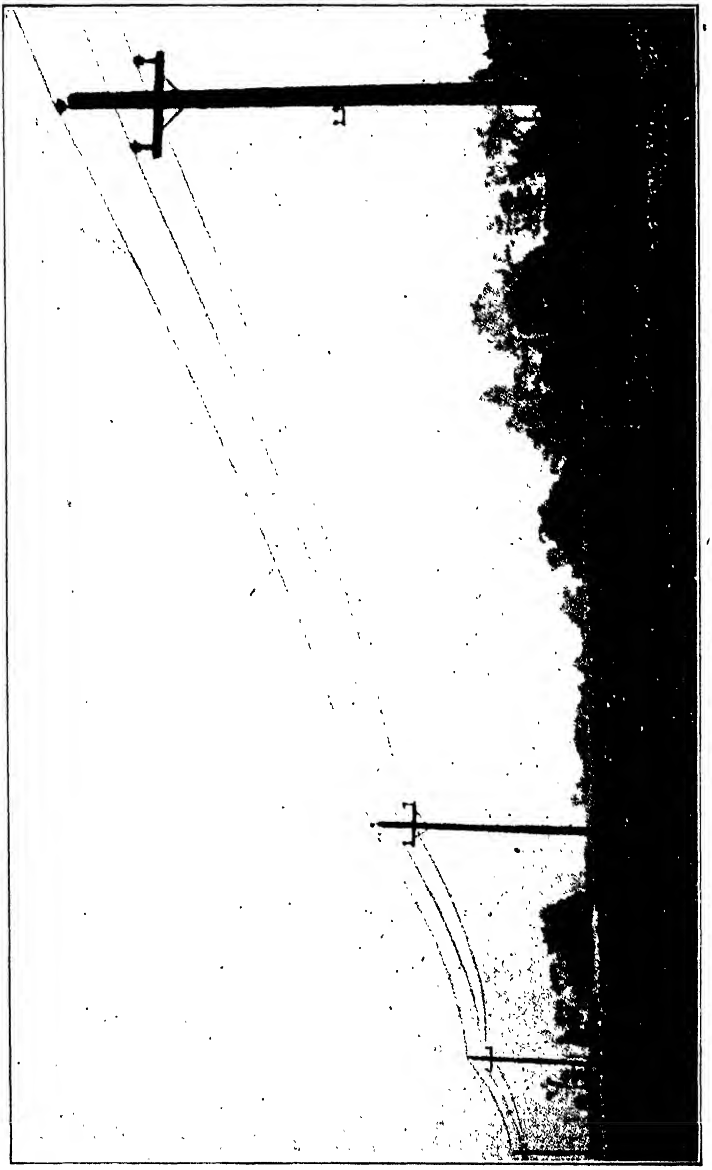


FIG. 28.—Showing good example of short-span wood-pole line construction; excellent location, with equal supportspacing, even sag of conductors, equal height of line supports and conductors pulled up to the maximum allowable tension.

sag table (such as Table XXXVI.) or chart (such as fig. 29 plotted from Table XXXVI.), the sag of conductor for the particular span and temperature is found. Attach tags to each of the two poles to

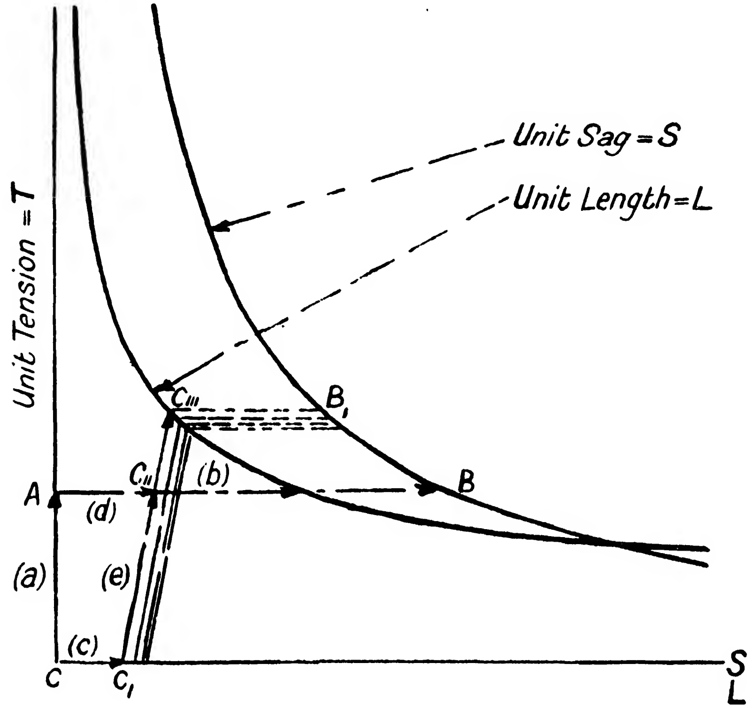


FIG. 29.—Sag and tension chart (based on the catenary curve) for unit span, etc.

Note.—Where problems involve conditions of changing temperature, fig. 29 is much improved upon by plotting a set of curves from the values given in Table XXXVI., and then plot on the same paper another set of curves (the two sets of curves intersecting) for stretch at definite intervals of temperature. The stretch curve is for conditions corresponding to given temperatures when the load on the conductor is varied. The chart thus comprises two axes. To use the chart, first locate the stress (or tension) value, then the corresponding sag as in the case of the chart shown in fig. 29. Then, to find the sag under the stringing condition of load, follow the stretch curve to the axis: thus, for a stringing temperature of 60° F. follow the axis for this temperature and return on another constant-temperature line to the load represented by the weight of the bare conductor in still air. This point gives the stress (or tension) and the corresponding sag for the stringing condition. The chart is equally useful for any loading condition, also, the temperature scale can be moved to suit any value of coefficient of expansion, and therefore one chart can be used for all conductor-materials.

sag distance below the respective conductor supports, and sight from one batten or target to the other. After the conductor has been properly sagged, its lowest point should line in with the two battens or targets. When sagging is done with dynamometer, the resultant sag may have to be checked over again by means of the sighting method. All grips, draw-tongs, come-alongs, etc. used should either have copper jaws or be used in conjunction with copper shims to prevent injury to the conductor. In cases where conductors of different sizes are strung to the same sag, the chosen sag should be such as to keep the smallest conductor involved within safe practical limits for sag requirements and conductor clearances.

In calculating the sag it is assumed that the conductors are to be loaded with the maximum loading of ice and wind, and under such conditions to be stressed to the maximum allowable tension as mentioned on p. 74. Where different sizes of conductor are strung on the same pole, conditions may alter this. When conductors are stressed to this maximum allowable tension they are longer than in the unstressed state. And if the temperature goes up, the expansion of the conductor will cause an increase in the sag, which within the limits of practical contraction in the conductor will decrease the tension, thus allowing a counter-contraction in the conductor, due to its elasticity. At a certain sag the two tendencies will balance each other; hence the practical requirement is to determine the point at which this will occur. Another condition is that in case the maximum load is removed, the decreased load on the conductor will allow it to contract, which, by decreasing the sag, increases the stress, thus tending to increase the length and along with it the sag; but at a certain point these also will balance each other. Under these different conditions the practical problem is to determine the unstressed length and then to determine the unstressed length at other temperatures or under other conditions. Thus, knowing the unstressed length, the amount of sag and stretch is easily found (see p. 174). Values of tension and sag can be given in the form of tables or charts; the latter are more valuable because intermediate values are usually given. Some of the charts which may be plotted from tables and/or data are:

> Plot curves for each size of conductor and for the more generally used stringing temperatures in terms of span-length and sag. In this way the values of sag for any span-length are found; or
>
> Plot curves for one size of conductor, and for different temperatures and loading values; in terms of span-length and sag. In this way the values of sag for any span and for different temperatures are found; or
>
> Plot a curve for any size of conductor and one span (the span in more general use) in terms of sag and a full range of temperatures. As the majority of lines often keep to one or

two sizes of conductor and to two or three "average" spans, two or three curves of this nature should be found very useful in the field; or

Plot sag values for the spans used and for different temperatures in terms of standard sizes of conductor and sag values; or

Plot sag and length (unit) values in terms of tension (unit) values for (unit $=1{\cdot}0$ ft.) span from Table XXXVI. Plotted on logarithmic paper, the sag and length values would practically form a straight line throughout; or

Plot sag and tension curves for each size of conductor in terms of different loadings and different temperatures and different spans. In this way any intermediate value of sag and tension is found; or

Draw a catenary chart from the length, sag, and stress values given in Table XXXVI. and calculate from $L_t = L_0 (1 + a\,t)$ the length (L_t) due to expansion with temperature changes; the required sag and tension is then obtained by drawing lines for the different temperatures parallel to the reference lines C′C″ (see fig. 29). This is a quick and accurate method for obtaining sags and tensions due to changes in temperature and/or load. That is to say:

First step = obtain unit tension from a knowledge of the maximum allowable tension, loading, and the actual span-length (see Table XXXVI.).

Second step = reference line AB = parallel line (with base) drawn from value T = length L (see Table XXXVI.).

Third step = unstressed length L_0 which may be above or below unity (see following example).

Fourth step = actual length of conductor *only* taken along the base C, marked AB on reference line.

Fifth step = desired reference line C′C″ = straight line drawn from C′C″ intersecting C″.

Sixth step = unit tension and corresponding sag for bare conductor in still air at datum ° F. = C‴ and B′.

Seventh step = calculate lengths L_t for different temperatures and mark on base line CC′; draw respective values parallel to reference line C′C″, and parallel lines (horizontally) for the desired respective sag and tension values C‴, B′, etc.

TABLE XXXVI.

SAG AND TENSION VALUES FOR BARE HARD-DRAWN COPPER CABLE; DERIVED FROM THE CATENARY EQUATION.

[*Note.*—The tension, length, and sag values [or (*a*), (*b*), and (*c*) respectively] are quite accurate, and may be used for the making of a *catenary chart*; can be used for every combination of material, size, weight, loading, and span-length.]

$$(a)=\frac{Y}{l} \text{ where } Y=\frac{T}{W};\ (b)=L;\ (c)=S;\ (d)=L_0=L-e \text{ where } e=\frac{(T/A)}{e'};\ (e)=L_0+q \text{ where } q=\frac{e}{W/w};\ e'=18{,}000{,}000.$$

A. \ *l*.		100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
0·75	*a*	50·464	25·232	16·8213	12·616	10·0928	8·4106	7·20914	6·308	5·6071	5·0464
	b	1·000017	1·000066	1·000148	1·000262	1·000410	1·000591	1·000805	1·001052	1·001333	1·001648
	c	0·002478	0·004956	0·006844	0·009915	0·012398	0·014885	0·017374	0·019869	0·022368	0·024873
	d	0·998456	0·998505	0·998587	0·998701	0·998849	0·999030	0·999244	0·999491	0·999772	1·000087
	e	0·999575	0·999624	0·999706	0·999820	0·999968	1·000149	1·000363	1·000610	1·000891	1·001206
0·60	*a*	47·477	23·7385	15·8257	11·86925	9·4954	7·912833	6·78243	5·93462	5·27522	4·7477
	b	1·000019	1·000074	1·000167	1·000296	1·000463	1·000668	1·000910	1·001189	1·001507	1·001864
	c	0·002634	0·005267	0·007902	0·010540	0·01318	0·015824	0·018472	0·021126	0·023785	0·026452
	d	0·998453	0·998508	0·998601	0·998730	0·998897	0·999102	0·999344	0·999623	0·999941	1·000298
	e	0·999493	0·999548	0·999641	0·99977	0·999937	1·000142	1·000384	1·000663	1·000981	1·001338
0·50	*a*	46·268	23·134	15·4226	11·567	9·2736	7·71133	6·609714	5·7835	5·14088	4·6268
	b	1·000020	1·000078	1·000176	1·00031	1·000486	1·000705	1·000958	1·001253	1·001588	1·001963
	c	0·002703	0·005405	0·008109	0·010815	0·0134956	0·016260	0·018957	0·021681	0·024412	0·027150
	d	0·998395	0·998453	0·998501	0·998685	0·998861	0·999080	0·999333	0·999627	0·999963	1·000337
	e	0·999426	0·999484	0·999582	0·999716	0·999892	1·000111	1·000364	1·000659	1·000994	1·001369
0·40	*a*	42·846	21·423	14·282	10·7115	8·5692	7·141	6·12086	5·35575	4·7607	4·2846
	b	1·000023	1·000091	1·000205	1·000364	1·000569	1·00082	1·001118	1·001462	1·001853	1·002292
	c	0·002919	0·005837	0·008757	0·011681	0·014608	0·017541	0·020179	0·023425	0·026379	0·029342
	d	0·998398	0·998466	0·998580	0·998739	0·998944	0·999195	0·999493	0·999837	1·000228	1·000667
	e	0·999359	0·999427	0·999541	0·999700	0·999905	1·000156	1·000454	1·000798	1·001189	1·001628
0·30	*a*	39·368	19·684	13·1227	9·842	7·8736	6·56133	5·624	4·921	4·3742	3·9368
	b	1·000027	1·000108	1·000242	1·00043	1·000674	1·000972	1·001325	1·001734	1·002198	1·00272
	c	0·003176	0·006353	0·009532	0·012715	0·015903	0·019098	0·02230	0·025512	0·028734	0·031969
	d	0·998365	0·998446	0·99858	0·998768	0·999012	0·999310	0·999663	1·000072	1·000536	1·001058
	e	0·999251	0·999332	0·999466	0·999656	0·999898	1·000196	1·000549	1·000958	1·001422	1·001944

0·25	*a*	35·274	17·637	11·758	8·8185	7·0548	5·879	5·039143	4·4093	3·9193	3·5274
	b	1·000034	1·000134	1·000302	1·000537	1·000841	1·001212	1·001653	1·002163	1·002745	1·003398
	c	0·003543	0·007082	0·010639	0·014194	0·017756	0·021327	0·024909	0·028503	0·032113	0·03574
	d	0·998452	0·998552	0·998720	0·998955	0·999259	0·999629	1·000071	1·000581	1·001163	1·001816
	e	0·999233	0·999333	0·999501	0·999736	1·000040	1·000410	1·000852	1·001362	1·001944	1·002597
0·225	*a*	33·577	16·789	11·19233	8·39425	6·7154	5·59616	4·796714	4·19713	3·7307	3·30577
	b	1·000037	1·000148	1·000333	1·000593	1·000928	1·001338	1·001825	1·00239	1·003033	1·003877
	c	0·003725	0·007449	0·011178	0·014913	0·018657	0·022412	0·026179	0·029961	0·033761	0·038181
	d	0·998504	0·998615	0·998800	0·99906	0·999395	0·999805	1·000292	1·000857	1·001500	1·002344
	e	0·999248	0·999359	0·999544	0·999804	1·000139	1·000549	1·001036	1·001601	1·002244	1·003088
0·20	*a*	32·149	16·0745	10·71633	8·03725	6·4298	5·35816	4·592714	4·018625	3·57211	3·2149
	b	1·000041	1·000165	1·000364	1·000647	1·001012	1·001461	1·001993	1·002009	1·003312	1·004104
	c	0·003889	0·00778	0·0116773	0·015578	0·01949	0·023414	0·027353	0·031309	0·035294	0·0392832
	d	0·998425	0·998546	0·998748	0·999031	0·999397	0·999845	1·000377	1·000993	1·001696	1·002488
	e	0·999137	0·999258	0·99946	0·999743	1·000108	1·000557	1·001089	1·001705	1·002408	1·0032
0·175	*a*	30·195	15·0975	10·065	7·54875	6·039	5·0325	4·31357	3·77438	3·355	3·0195
	b	1·000046	1·000183	1·000412	1·000734	1·001148	1·0016569	1·002261	1·002962	1·003762	1·004663
	c	0·004141	0·008289	0·012432	0·016589	0·020759	0·024945	0·029143	0·028364	0·037611	0·041883
	d	0·998426	0·998563	0·998791	0·999114	0·999528	1·000037	1·000641	1·001342	1·002142	1·003043
	e	0·999095	0·99923	0·999461	0·999783	1·000195	1·000706	1·00131	1·002011	1·002811	1·003712
0·15	*a*	28·02	14·01	9·34	7·005	5·604	4·67	4·00286	3·503	3·11333	2·802
	b	1·000053	1·000213	1·000479	1·000849	1·001334	1·001927	1·00263	1·003447	1·004381	1·005433
	c	0·004463	0·008927	0·013407	0·017848	0·02238	0·026896	0·031434	0·035998	0·040592	0·045222
	d	0·998423	0·998583	0·998849	0·99922	0·999704	1·000297	1·001000	1·001817	1·002751	1·003803
	e	0·99904	0·999200	0·999466	0·999837	1·000321	1·000914	1·001617	1·002434	1·003368	1·00442
0·125	*a*	25·734	12·867	8·578	6·4335	5·1468	4·289	3·676286	3·21675	2·859333	2·5734
	b	1·000063	1·000252	1·000568	1·001011	1·001584	1·002288	1·003125	1·004098	1·005212	1·006469
	c	0·004859	0·009721	0·014593	0·019479	0·024383	0·029312	0·032681	0·039259	0·044290	0·049365
	d	0·998404	0·998593	0·998909	0·999352	0·999925	1·000630	1·001466	1·002439	1·003553	1·004810
	e	0·998960	0·999159	0·999465	0·999908	1·000481	1·001186	1·002022	1·002995	1·004109	1·005366
0·10	*a*	22·593	11·2965	7·531	5·64825	4·5186	3·7655	3·22757	2·824125	2·510333	2·2593
	b	1·000817	1·000327	1·000737	1·001314	1·002059	1·002977	1·004071	1·005346	1·006791	1·008465
	c	0·005535	0·011075	0·016629	0·022204	0·027806	0·033444	0·039125	0·044856	0·050648	0·056509
	d	0·998398	0·998643	0·999053	0·999630	1·000375	1·001292	1·002387	1·003662	1·005107	1·006601
	e	0·998898	0·999143	0·999553	1·000130	1·000875	1·001792	1·002887	1·004162	1·005607	1·007101

TABLE XXXVI.—*continued.*

A. \ l.		100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
0·075	*a*	17·82	8·910	5·940	4·455	3·564	2·970	2·5457	2·2275	1·980	1·782
	b	1·000131	1·000526	1·001187	1·002119	1·003328	1·004816	1·006615	1·008718	1·011150	1·013930
	c	0·007017	0·014048	0·021107	0·028207	0·035366	0·042569	0·049920	0·057352	0·064913	0·072627
	d	0·998471	0·998866	0·999527	1·000459	1·001668	1·003156	1·004955	1·007058	1·009490	1·012270
	e	0·998867	0·999262	0·999923	1·000855	1·002064	1·003552	1·005351	1·007454	1·009886	1·012666
0·05	*a*	13·624	6·8120	4·54133	3·406	2·7248	2·270665	1·9463	1·7030	1·5138	1·3624
	b	1·000225	1·000902	1·002038	1·003649	1·005753	1·008378	1·011560	1·015345	1·019794	1·025986
	c	0·009181	0·918392	0·027666	0·037037	0·046360	0·056214	0·066104	0·076263	0·086749	0·097640
	d	0·998518	0·999195	1·000331	1·001942	1·004046	1·006671	1·009852	1·013638	1·018087	1·024279
	e	0·998821	0·999498	1·000634	1·002245	1·004349	1·006974	1·010155	1·013941	1·018390	1·024582
0·025	*a*	8·130	4·065	2·710	2·0325	1·626	1·355	1·16143	1·01625	0·90333	0·8130
	b	1·000632	1·002550	1·005817	1·010551	1·016913	1·025293	1·035988	1·049940	1·068311	1·093891
	c	0·015499	0·030947	0·046801	0·063132	0·080107	0·098248	0·117623	0·139217	0·163840	0·193699
	d	0·998844	1·000773	1·004040	1·008774	1·015136	1·023516	1·034211	1·048163	1·066534	1·092114
	e	0·999025	1·000954	1·004221	1·008955	1·015317	1·023697	1·034392	1·048344	1·066715	1·092295

(*a*) Unit tension.
(*b*) Length for maximum tension and load.
(*c*) Sag for maximum tension and load.
(*d*) Unstressed length at zero temperature.
(*e*) Actual length (with ice and wind) at zero temperature.

Note.—Elastic stretch = specific extension e = (*b*) − (*d*) = L − L_0.

Experience would seem to indicate that one of the most helpful methods for showing the relations between length, sag, and tension is to prepare a table on the basis of standard sizes of the most commonly used conductors (the hard-drawn copper conductor) in terms of 1-ft. span, and conductor of 1 lb. per foot of weight for unit length, unit sag, and unit tension. These values, calculated from the catenary equation, are given in Table XXXVI. As a check on other calculations, tables, and charts (based on other formulæ) they should prove useful. *They are of special value for preparing a catenary chart for any combination of material, size, weight, span, etc.*

If the load of W lb. per foot stretches the material from $L_0=(d)$ to L, a load of w will stretch it $w/W(L-L_0)$, which, added to L_0, gives the length (*e*) of the conductor for w load—that is, $L_0+w/W(L-L_0)=L_1$. This value should be plotted on the $Y/l=(a)$ line, and through this point and (*d*) value a straight line is drawn to the unit-length curve. Its intersection with the unit-length curve gives the value (*e*). With variations in temperature first determine (*d*), then the length resulting from the change in $t°$ is $=L_t=L_0(1+\alpha t)$. These unstressed lengths are then marked off on the unit-length scale and straight lines drawn parallel to L_0 and L_1 lines; the coincident values of unit sag and unit tension are then available. Actually, after obtaining values (*a*) to (*e*) for any material, size, span, weight, and loading, then proceed just the same as for method fig. 29; or, preferably, plot curves in terms of constant-temperature values.

Note.—L_0 = the original length of conductor in feet; a = coefficient of expansion for the material per ° F.; t = number of ° F. change in temperature.

For any loading condition such as $\frac{1}{4}$-in. ice and 8-lb. wind (see Table VII.), or/and for any conductor metal such as steel-cored aluminium (see Table XIX.), or/and copper-alloy conductor which is more desirable than the latter (see Table XXII.), all that is necessary is to plot the tension (*a*), the length (*b*), and the sag (*c*), as given here for copper, and $\frac{1}{2}$-in. ice and 8-lb. wind loading. If logarithmic paper is used, the curves (*b*) and (*c*) will form a straight line and will cross at one point; if plotted on cross-section paper they will take the form of a parabola as shown in fig. 29. Use a large sheet of paper if close accuracy is desired.

Calculate (*a*) value which is very simple, then, for any loading condition such as $\frac{1}{4}$-in. ice and 8-lb. wind, the values of (*b*) and (*c*) are read off at the points where (*a*) values intersect (*b*) and (*c*) curves respectively. The unstressed length (*d*) depends on the modulus of elasticity of the conductor metal as is given by value (*b*) divided by $1+(T/Ae)$, this gives the unstressed length L_0. The coefficient of expansion also depends on the kind of conductor metal, and under this condition for a temperature rise, *t*, above datum we obtain (*e*) which is $L_0(1+at)$. Whether for 40°, 60°, 80°, 100°, or 120°, respectively, the values of (*e*) are calculated and the respective lines $C_{,}$, $C_{,,}$, $C_{,,,}$ are drawn; these are drawn parallel to each other as shown in fig. 29. In this way both sag and tension values for any temperature and any loading and any conductor metal are obtained; the respective values are then multiplied into the span-length to give the true values desired.

Let us take the following example for a loading condition of $\frac{1}{4}$-in. ice and 8-lb. wind.

Example.—It is proposed to erect a 0·05 sq. in. (3/·147) h.d. bare copper conductor on a wood-pole line with average spans of 200 ft.—the conductors to be erected in such a way that the tension shall not exceed the ultimate breaking strength of 61,460 lb./sq. in., or $(61{,}460\times 0{\cdot}05)/2=1536$ lb. at 22° F. The requirements are to find the sag and tension (or stress) at different changes of temperature and $\frac{3}{16}$-in. ice-loading; see p. 73 for $\frac{3}{16}$-in. ice-loading.

Constants.—$A=0{\cdot}05$ sq. in.; $d=0{\cdot}317$ in.; $d'=0{\cdot}187$ in.; $e=18{,}000{,}000$ lb./sq. in.; $w=0{\cdot}2002$ lb.; $w''=0{\cdot}318$ lb.; $W=0{\cdot}5555$ lb./ft. of length; $a=0{\cdot}0000093$ per °F.; $T=1536$ lb.; $l=200$ ft.

Then, in terms of allowable tension, the tension on a 1·0 ft. span is

$$T'=\frac{T}{Wl}=\frac{1536}{0{\cdot}5555\times 200}=13{\cdot}82 \text{ lb.}$$

The sag for the corresponding span (1·0 ft. in length) is given by the *plotted values* (*a*), (*b*), and (*c*) of Table XXXVI. (which are for ½-in. ice), and is 0·00904; making total sag

$$S = 200 \times 0{\cdot}00904 = 1{\cdot}808 \text{ ft.}$$

Checking by the parabola method (see p. 74) we have

$$S = \frac{200^2 \times 0{\cdot}5555}{8 \times 1536} = 1{\cdot}808 \text{ ft.}$$

The length of the conductor for the span 1·0 ft. in length is also given by the *plotted values* (*a*), (*b*), and (*c*) of Table XXXVI., and is 1·00022; making the total length

$$L = 200 \times 1{\cdot}00022 = 200{\cdot}044 \text{ ft.}$$

Checking by the parabola method (see p. 74) we have

$$L = 200 + \frac{8 \times 1{\cdot}808^2}{3 \times 200} = 200{\cdot}0435 \text{ ft.}$$

The unstressed length with all the tension removed, is

$$L_0 = 1{\cdot}00022 - \frac{1536/{\cdot}05}{18{,}000{,}000} = 0{\cdot}9985 \text{ ft.}$$

hence, actual length for the span is $200 \times 0{\cdot}9985 = 199{\cdot}7$ ft.

Checking by the parabola method (see p. 74) we have

$$L_0 = \frac{200{\cdot}0435}{1 + \dfrac{1536}{0{\cdot}05 \times 18{,}000{,}000}} = 199{\cdot}7 \text{ ft.}$$

The actual unstressed length, without wind or ice, for a span 1·0 ft. in length is

$$L' = L_0 + \frac{(T/A)/e}{W/w} = 0{\cdot}9985 + \frac{(1536/{\cdot}05)/18{,}000{,}000}{0{\cdot}5555/{\cdot}2002}$$

$$= 0{\cdot}9985 + \frac{0{\cdot}0017}{1{\cdot}172} = 0{\cdot}999 \text{ ft.}$$

With a rise in temperature, the length will increase due to expansion; therefore for (say) 120° F. rise in temperature, the length of span will be

$$L_t = L_0(1 + a\,t) = 0{\cdot}9985(1 + 0{\cdot}0000093 \times 120) = 0{\cdot}9997 \text{ ft.,}$$

hence, the length of span is $200 \times 0{\cdot}9997 = 199{\cdot}94$ ft.

This latter is the calculation to make for the different temperatures; then draw in the respective values for 1·0 ft. span (unit basis) on the chart. These new lines should be *drawn in pencil* so as to retain the chart for future use and for different types of conductors, metals, loadings, etc. These new lines intersect the sag (S) and tension (T) curves, at which points the desired values of sag and tension (or stress) can be obtained direct from the plotted values (*b*) taken from Table XXXVI. in terms of (*a*), which is the respective corresponding tension desired. For more detail see end of Chapter XI., *Overhead Electric Power Transmission Engineering*, by same author.

The following sag and tension values are for *copper alloy* [1] conductors, which offer special merits for rural distribution lines:

TABLE XXXVII.

SAG AT CENTRE OF SPAN AND MAXIMUM TENSION AT TEMPERATURES AND FOR SPAN-LENGTHS INDICATED. SUPPORTS AT SAME LEVEL.

Length of Span.	Condition of Loading.					
	½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 0° F.		½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 32° F.		½-in. Ice, No Wind, at 32° F.	
Feet.	Sag * (Ft.).	Tension (Lb.).	Sag * (Ft.).	Tension (Lb.)	Sag (Ft.).	Tension (Lb.).
100	0·50	3060	0·58	2670	0·41	2610
200	2·02	3060	2·26	2740	1·70	2530
300	4·55	3060	5·00	2780	3·96	2430
400	8·09	3060	8·67	2860	7·29	2350
500	12·68	3060	13·37	2900	11·74	2290

* In plane of resultant.

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[1] Made by Anaconda Copper Mining Company, N.Y., U.S.A.

[TABLES.

TABLE XXXVII.—*continued.*

Length of Span.	Condition of Loading—No Wind, no Ice.									
	100 Feet.		200 Feet.		300 Feet.		400 Feet.		500 Feet.	
Temperature ° F.	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).
−20	0·13	3230 [1]	0·56	3020	1·60	2560	3·30	2050	6·60	1580
0	0·14	2970	0·62	2700	1·66	2290	3·66	1840	7·28	1450
20	0·16	2710	0·68	2460	1·82	2080	4·07	1660	7·91	1330
40	0·17	2450	0·76	2210	2·05	1850	4·55	1490	8·58	1230
60	0·19	2190	0·86	1960	2·32	1640	5·05	1340	9·24	1140
80	0·22	1930	0·98	1720	2·63	1440	5·59	1210	9·90	1070
100	0·25	1680	1·13	1490	3·00	1260	6·16	1100	10·55	1000
120	0·30	1420	1·33	1270	3·42	1110	6·71	1010	11·18	947

[1] 170 lb. over 50 per cent. breaking strength.

Constants : Dead weight 0·3370 lb./ft.
Dead weight, plus ½-in. ice, 0·8555 lb./ft.
Horizontal load, 8-lb. wind on iced wire, 0·88906 lb./ft.
Maximum load, plane of resultant 1·2338 lb./ft.
Area of wire 0·08746 sq. in. Diameter 0·3336 in.
Young's Modulus 16,000,000 lb. per sq. in.
Coefficient of expansion 0·0000094 per ° F.
Diameter of wire 0·3336 in. round.
Loading class = ½-in. ice, 8-lb. wind, at 0° F.
Breaking strength 6120 lb.
Maximum tension 3060 lb.
Elastic limit 3670 lb.

TABLE XXXVIIA.

SAG AT CENTRE OF SPAN AND MAXIMUM TENSION AT TEMPERATURES AND FOR SPAN-LENGTHS INDICATED. SUPPORTS AT SAME LEVEL.

Length of Span. (Feet.)	Condition of Loading.					
	½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 0° F.		½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 32° F.		½-in. Ice, No Wind, at 32° F.	
	Sag [1] (Ft.).	Tension (Lb.).	Sag [1] (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).
100	0·58	2470	0·67	2170	0·46	2100
200	2·34	2470	2·58	2240	0·96	2000
300	5·27	2470	5·70	2290	4·55	1900
400	9·39	2470	9·95	2330	8·45	1820

[1] In plane of resultant.

Length of Span.	Condition of Loading—No Wind, no Ice.							
	100 Feet.		200 Feet.		300 Feet.		400 Feet.	
Temperature, ° F.	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).
-20	0·13	2580 [2]	0·58	2300	1·64	1850	4·02	1340
0	0·14	2370	0·64	2090	1·82	1660	4·49	1200
20	0·15	2170	0·71	1890	2·04	1480	4·99	1080
40	0·17	1960	0·79	1690	2·31	1310	5·53	974
60	0·19	1750	0·90	1490	2·63	1150	6·08	885
80	0·22	1500	1·03	1300	2·99	1010	6·65	810
100	0·25	1340	1·20	1120	3·38	887	7·22	746
120	0·29	1140	1·41	955	3·86	784	7·78	693

[2] 110 lb. over 50 per cent. breaking strength.

Constants : Dead weight 0·2686 lb./ft.
Dead weight, plus ½-in. ice, 0·76489 lb./ft.
Horizontal load, 8-lb. wind on iced wire, 0·86526 lb./ft.
Maximum load, plane of resultant 1·1548 lb./ft.
Area of wire 0·06970 sq. in.
Young's Modulus 16,000,000 lb. per sq. in.
Coefficient of expansion 0·0000094 per ° F.
Diameter of wire 0·2979 in. round.
Loading Class = ½-in. ice, 8-lb. wind at 0° F.
Breaking strength 4940 lb.
Maximum tension 2470 lbs.
Elastic limit 2960 lb.

TABLE XXXVIIB.

SAG AT CENTRE OF SPAN AND MAXIMUM TENSION AT TEMPERATURES AND FOR SPAN-LENGTHS INDICATED. SUPPORTS AT SAME LEVEL.

Length of Span (Feet).	Condition of Loading.					
	½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 0° F.		½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 32° F.		½-in. Ice, No Wind, at 32° F.	
	Sag [1] (Ft.).	Tension (Lb.).	Sag [1] (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).
100	0·81	1590	0·92	1410	0·59	1320
200	3·26	1590	3·53	1470	2·60	1200
300	7·36	1590	7·77	1510	6·40	1110
400	13·14	1590	13·63	1530	12·03	1050

[1] In plane of resultant.

Length of Span.	Condition of Loading—No Wind, no Ice.							
	100 Feet.		200 Feet.		300 Feet.		400 Feet.	
Temperature, ° F.	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).
−20	0·13	1600[2]	0·67	1250	2·57	737	7·84	430
0	0·14	1470	0·75	1120	2·92	647	8·39	402
20	0·16	1340	0·84	998	3·33	569	8·93	378
40	0·17	1210	0·96	877	3·77	502	9·45	357
60	0·20	1080	1·11	760	4·21	449	9·95	340
80	0·22	950	1·29	650	4·70	403	10·43	324
100	0·26	823	1·53	550	5·17	367	10·90	310
120	0·30	696	1·81	464	5·63	337	11·37	298

[2] 10 lb. over 50 per cent. breaking strength.

Constants : Dead weight 0·1680 lb./ft.
Dead weight plus ½-in. ice 0·6255 lb./ft.
Horizontal load, 8-lb. wind on iced wire, 0·8237 lb./ft.
Maximum load, plane of resultant 1·0342 lb./ft.
Area of wire 0·04358 sq. in.
Young's Modulus 16,000,000 lb. per sq. in.
Coefficient of expansion 0·0000094 per ° F.
Diameter of wire 0·2356 in. round.
Loading Class = ½-in. ice, 8-lb. wind, at 0° F.
Breaking strength 3181 lb.
Maximum tension 1590 lb.
Elastic limit 1900 lb.

TABLE XXXVIIc.

SAG AT CENTRE OF SPAN AND MAXIMUM TENSION AT TEMPERATURES AND FOR SPAN-LENGTHS INDICATED. SUPPORTS AT SAME LEVEL.

Length of Span (Feet).	Condition of Loading.					
	½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 0° F.		½-in. Ice, 8 Lb. per Sq. Ft. Wind Pressure, at 32° F.		½-in. Ice, No Wind, at 32° F.	
	Sag [1] (Ft.).	Tension (Lb.).	Sag [1] (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).
100	1·14	1040	1·26	946	0·80	834
200	4·59	1040	4·86	987	3·77	710
300	10·40	1040	10·76	1010	9·37	646

[1] In plane of resultant.

Length of Span.	Condition of Loading—No Wind, no Ice.					
	100 Feet.		200 Feet.		300 Feet.	
Temperature, ° F.	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).	Sag (Ft.).	Tension (Lb.).
-20	0·14	965	0·99	536	6·07	197
0	0·15	893	1·14	464	6·50	184
20	0·16	811	1·34	395	6·91	173
40	0·18	729	1·59	334	7·29	164
60	0·20	648	1·88	281	7·69	156
80	0·23	567	2·22	239	8·06	149
100	0·27	487	2·56	207	8·42	143
120	0·33	408	2·93	181	8·77	137

Constants : Dead weight 0·1059 lb./ft.
Dead weight plus ½-in. ice 0·5332 lb./ft.
Horizontal load, 8-lb. wind on iced wire, 0·7913 lb./ft.
Maximum load, plane of resultant 0·95418 lb./ft.
Area of wire 0·02748 sq. in.
Young's Modulus 16,000,000 lb. per sq. in.
Coefficient of expansion 0·0000094 per ° F.
Diameter of wire 0·1870 in. round.
Loading Class = ½-in. ice, 8-lb. wind, at 0° F.
Breaking strength 2088 lb.
Maximum tension 1044 lb.
Elastic limit 1250 lb.

CHAPTER V.

THE DISTRIBUTION SYSTEM.

For the transmission of energy in bulk, three-phase is more economical and more useful than single-phase. The single-phase 3-wire and the three-phase 4-wire with earthed neutral in each case require the same amount of copper per kW for the same voltage between phase and neutral. Hence, the single-phase 3-wire system is about as economical in copper as the three-phase 4-wire system. For equal voltage between phase and earth, the amount of copper per kW in the three-phase 3-wire system is between 2·25 and three times more than that in the three-phase 4-wire system for equal percentage voltage drop. For equal voltage between phase-conductors the single-phase 3-wire system requires 37 per cent. more copper than is required for the three-phase 4-wire system, with neutral wire of the same size in each case, this being the more correct total conductor-area comparison.

For simplicity of system outlay and best system voltage-balance, the three-phase 4-wire system of distribution has advantages over all other systems. It is the most successful for both power and lighting purposes regardless of load balance, because single-phase regulation can be adjusted to give a constant voltage at any point on the line regardless of the load on the phases. It is the system that can be successfully used for supplying all the current over one circuit for any area, whether it is used for lighting, power, or heating, and the diversity and load factors are improved and investment costs decreased.

For rural service we may start out single-phase and load it up independent of the other phases; then run another phase-conductor when load requirements demand, and finally the third-phase conductor. It is therefore specially suited to rural or scattered districts where low first cost, difficulties in balancing loads, and good regulation are the rule, and where the system, taken as a whole, can be constructed piecemeal and yet require the least modification to complete the whole – this we obtain by use of the three-phase 4-wire system.

For primary and secondary distribution, the star-star connection of transformers offers the cheapest construction, and long practice has proved this method to give practically all that is desired. Also, the best practice points towards three-phase 4-wire *primary* **and** *secondary* **distribution with single-phase taps; see also fig. 32A.**

The two-phase (or *quarter*-**phase) inter-connected (see p. 202, last item of figures) system sometimes referred to as four-phase, will come into more general use for distribution purposes in countries like U.S.A. It is a system possessing outstanding merits; also see fig. 32B.**

The choice of a particular system of distribution is determined by a close study of relative simplicity and economy, the nature of the load, the extent of the area to be covered, and other considerations.

When the whole or the bulk of power is to be distributed in a congested area (or areas) where the heavy current necessitates the use of very large-sized conductors, alternating current is prohibited by the *reactive* voltage drop, and, where power is to be distributed over a relatively large and scattered area (or areas), direct current is prohibited by the ohmic voltage drop and/or excessive cost of copper and other conditions; the amount of copper required varying inversely as the square of the voltage between conductors.

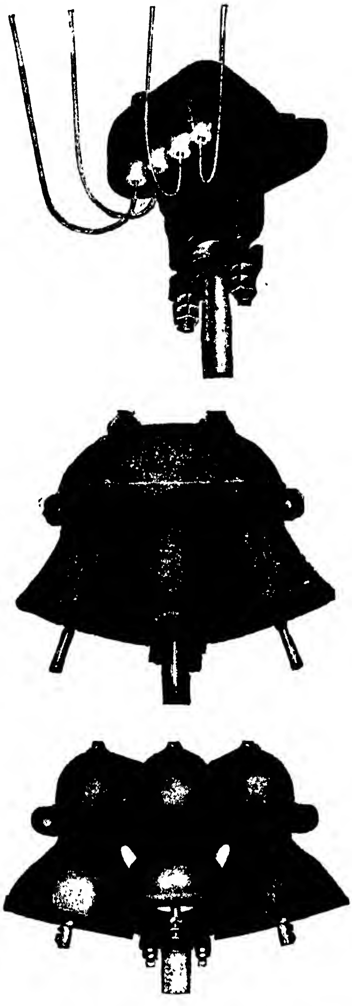

FIG. 30.—Terminal boxes. (*Henley.*) *Top view* is inverted pole type for 4-core, 660 volt, pilot cables. *Middle view* is inverted out-door type for 3-core, 6600 volts. *Lower view* is inverted out-door type for 3-core, 11,000 volt cables.

As an illustration of the effect of voltage we may take a single-phase 2-wire small-sized feeder, *i.e.* a feeder which is to transmit 100 kVA a distance of 1000 ft., allowing 5·0 per cent. voltage drop. For the different voltages we get the relations:

Voltage on Feeder.	Line Drop in Volts.	Size of Feeder in Square Inches.	Relative Amount of Copper Required.
12,000	600	0·0025	1·0
6,000	300	0·01	4·0
3,000	150	0·04	16·0
480	24	0·15	60·0
240	12	0·60	240·0

That is, 240 times more copper is required at 240 volts to deliver the same load the same distance, with the same percentage volts drop, than for 12,000 volts.

It is not so much the question of designing the most economical distribution system as of determining the best system to put in, having in view, of course, all present and future requirements. In deciding on any system it is advisable to look well ahead over a number of years and to plan a system and initially to lay it down, so that it is capable of handling the load densities for a number of years to come, and so to lay out the distribution that it will always be capable of expansion for the least capital outlay and with as few changes or modifications as possible.

In this and in certain other countries the urban areas will have underground distribution, and whether underground or overhead, for a town of some size the entire system will take supply from the generating station or a main sub-station as three-phase current. The system taken as a whole may have one or more transformations (the former being *direct* while the latter is *indirect*), that is:

The system may take supply from a main transmission line and feed into a main sub-station, and from the main sub-station step down for supply to feeders, which in turn feed centres of distribution where the current is again stepped down to supply the consumer's mains ; or,

The transmission line may feed into several sub-stations, and feeders extend from each of these sub-stations to transforming centres (which may be vault-, pole-, or structure-type) to supply the secondary (low-voltage) network or mains for consumer's services; or, The transmission lines may feed centres of distribution direct and/or pole-type transformers, and from these supply direct the secondary (low-voltage) network.

This country is about to start an era of electricity distribution on a large scale and under government control—this being the only possible way to bring about the long-delayed unification of systems, etc., and is the best means for meeting resulting expected strenuous public opposition, for a time at least. The scheme for the 132,000 volt government-controlled overhead main transmission lines, and the system of electricity supply, will probably take the form of best practice, such as:

(*a*) Main transmission lines arranged to interconnect *selected* generating stations.

(*b*) Transmission lines to supply the main sub-stations —preferably fed from two sources of supply—the stations to serve for switching and for transforming down the voltage.

(*c*) Lines run out from the main sub-stations to smaller transforming stations, at a suitable voltage (perhaps 33,000, 22,000, or 11,000 volts).

(*d*) Feeders run out from the transforming centres to supply vault and/or pole-type transformer installations, thence from low-voltage secondary mains to consumers, or/and to large consumers direct.

(*e*) Or, from the transforming centres, secondary main distributors will be run to supply consumers direct.

Depending on the magnitude of the transmission system and/or voltage and the area to be covered, etc., there may be one or more transformations. The one-transformation (or direct) method will be the cheaper for certain rural districts. The multi-transformation (or indirect) method may more generally be the best, and be most flexible and most economical where areas of a certain size are chosen and transforming centres located at the load centres respectively, so that one or more areas and transforming centres may be chosen to feed a high-pressure system which in turn supplies one or more primary feeders, just as in the direct method, with distribution pole-type transformers.

For this country, the latter method (the indirect method) will be the method more generally adopted, as, among various advantages, it makes possible the best selection of routes and/or wayleaves. Also, for a given range of load densities it is more economical than the direct method (one-transformation method), which has the disadvantage of relatively greater length of high-pressure circuit, more distribution transformers, line equipment, etc., than the indirect method. The multi-transformation method also makes live-line maintenance unnecessary with loop-feeder scheme, and it makes a desirable arrangement for supplying rural and small towns from intermediate sub-stations (transforming centres) connected to an e.h.p. ring main, such as the main-transmission scheme proposed and about to be installed for the greater part of this country.

Maximum overall economy depends in the first place on adopting the right type of generating, transforming, and transmitting system, and the right type of combined distribution system so as to take full advantage of diversity of loads, also to obtain the highest load factor by the interconnection of stations carrying diversified loads and so forth. Commencing with the 132,000-volt grid we expect (by means of the indirect method) through the various links of the electrical chain to obtain the desired results by adoption of a distributing system to secure jointly the best results both financial and operating. The best and most economical layout for general distribution is the three-phase 4-wire system, in which the

> E.h.p. line side of transformers at generating station connected in *star* with neutral earthed and with primary *delta*, and e.h.p. line side of receiving stations connected in *star* with neutral earthed; or
>
> E.h.p. or h.p. primary feeder distribution side of transformers at the receiving station (transforming centres) are connected in *star* with neutral earthed, and carrying a neutral conductor; or/and
>
> E.h.p. or h.p. primary main distribution transformers connected in *star* with neutral conductor earthed at more than one point on the primary distribution system;
>
> M.p. and/or l.p. secondary side of distribution transformers connected in *star* with neutral conductor strung from pole to pole and earthed at consumer's connections.

The three-phase 4-wire system would be the most suitable for combined secondary distribution, in that, as distinct to any other single system, it is the most adaptable in every way, and it best meets practically all distribution requirements, in that:

> From its origin, the system starts out as the simplest and most economical for generation, transformation, and transmission.
>
> It offers the simplest and most economical primary distribution system for single or multi-transformation.

Of any polyphase system it requires the least number of conductors, with neutral conductor strung from pole to pole.

For the same kVA output it is the most economical in copper.

Voltages to earth and all phase-conductors have symmetrical relations (see p. 202).

There is a saving in the number of feeders and their supports; 66 to 80 per cent. of the number of feeders are required for the same kVA capacity.

It offers a symmetrical polyphase system.

Secondary voltages are suitable for both light and power.

Satisfactory light and power can be given over the same circuit (see also figs. 32 and 32A).

Line drop due to a balanced load will not cause distortion of the voltages either in magnitude or in phase.

Unbalance in secondary voltage caused by unbalanced loads is very small.

The investment cost per kVA delivered is low.

One conductor is neutral and is earthed in such a way as to limit the voltage of all other conductors to earth, and for secondary lighting to a value within safety limit to life.

The neutral conductor can be arranged in instances for use in emergency as a power (phase) conductor (see p. 214).

The neutral conductor can be used during normal operation for the purpose of protection of the line conductors and pole from lightning, and also serve for relaying purposes of protection.

The efficiency is high; higher than any other system.

The saving in the number of feeders is important, not only from possible public objections to more conductors and more crossarms and other line equipment; and, a less number of transformer stations are required for a given area or district or territory to be covered.

If a higher degree of reliability can be established in distribution lines, expensive duplication can be eliminated in rural areas by using the three-phase 4-wire system and arranging that the neutral conductor is used in emergency as a phase-feeder conductor. First of all we must design and construct a circuit that is the freest from flash-overs and bird trouble. A correctly designed wooden-pole construction will permit this, and it will permit the best results with a three-phase 4-wire circuit, and such a circuit may be as good or better than two circuits of the type, system, and construction in common practice at the present time in this country. Such a line would be cheaper and very much better not only from the operating standpoint but also from the earning standpoint. That is to say, have the wooden supports retain (at all times) the highest possible insulation of the wood, use wooden crossarms, and insulate the neutral from the pole. The primary *distribution* system would be three-phase 4-wire, but the main-*transmission* system would (for the present) be three-phase 3-wire; some of the relative advantages of these two systems being as follows:

	Three-phase 3-wire.	Three-phase 4-wire.
Voltage between phase-conductor and earth	100 per cent.	100 per cent.
Copper required when using three conductors for equal percentage power loss	100 ,,	33·3 ,,
Copper required when using four conductors of the same size for the three-phase 4-wire system . .	100 ,,	44·4 ,,
Relative economic size when using three conductors	100 ,,	57·7 ,,
Relative economic size for four conductors of equal size for the three-phase 4-wire	100 ,,	76·8 ,,

This clearly shows the necessity of running a fourth conductor and *using it properly* for both transmission and distribution, such as proposed in fig. 6.

The two problems, namely, *system* and *voltage*, mainly affect the general distribution from the sub-stations to the consumers. The system would, in many respects, be practically independent of the choice of voltage, because that offering the best set of combined light and power advantages, such as the most economical distribution, the longest, largest, and heaviest range of distribution, simplicity, greatest flexibility, and so forth, would be adopted in any case, independent of the voltage. As the choice will universally fall on the *three-phase* 4-*wire* system, there is still the voltage to settle, and this, for feeders, may be taken as ranging between the three standards of 11,000, and/or 6600, and/or 3300 volts respectively, depending on local conditions as to distance and so forth (see p. 12).

The next question is the type of distribution system; the primary supply would divide itself into the use of either radial feeders or ring mains, the choice will depend on the extent and form of the load area, the position and the spacing of the transforming centres with respect to load densities, etc. The secondary main would certainly be of the radial and/or the feeder types, depending on the form and extent of the respective and different load areas, load densities, etc.

In the case of most big extensions or change over from one system to another, there is always a likelihood of difference of opinion as to the voltage and kind of system that should be used for the primary distribution. There are certain limitations independent of distance which will govern the type to put in, but as a general rule the choice will fall on a system that

> Possesses the greatest flexibility.
>
> Will increase the capacity (in relation with other systems) of the *whole* system.
>
> Will permit satisfactory polyphase operation when one-phase conductor *and*/or one-phase transformer are put out of commission (see fig. 32A).
>
> Will provide the best, or better, or good service on remote extensions.
>
> Will permit a cheap construction; where the revenue derived from remote extensions and certain rural districts may not justify the expense of a three-phase, it would justify a single-phase line.

Also, the choice and the expense of a system will depend on

> The attitude of the Postmaster General, or the communication-system engineers, as their lines already occupy nearly all of the roads or highways in so far as this country is concerned.
>
> The objection of the Postmaster General to joint lines where the overhead circuits are operating in excess of a certain voltage, assuming, of course, that joint occupancy is allowable for lower-voltage lines. For this country this question is as yet quite remote for a.c. lines of any voltage.

We thus see that one of the most important problems is the determination of the most economical scheme for primary voltage distribution—not the main-line voltage or transmission voltage, nor the secondary voltage. For several reasons it depends on the method used, and we may, for example, adopt:

> A method in which an area of a certain size is chosen and a transformer sub-station located at the load centre; this

sub-station to be fed from the high-pressure system and in turn to supply one or more sub-station transformers and/or three-phase or three-phase 4-wire feeders. Such a method has the following advantages:

The system requires a less number of miles of high-pressure circuit.

It requires a shorter length of high-pressure circuit.

It requires less clearance from trees and buildings.

It offers better opportunity for arranging joint use of poles.

It makes a good arrangement for supplying rural districts from intermediate transformer stations or points.

The service rendered would be improved when feeders are equipped with automatic reclosing features.

In areas of high-load density the high-pressure feeders in combination with low-pressure secondary network would usually present the most economical arrangement.

Some few years ago the two-phase 4-wire system was widely used in certain countries, but has steadily been replaced by the three-phase system, which has proved to be the best and the most flexible. Until recently this country has been what might aptly be termed "a direct-current country" as compared with others, and there are many who still look with suspicion on the future electricity supply and distribution claiming general use of alternating currents. For congested areas and loads, direct-current distribution is all that can be desired, and long experience with this system has given practically all one desires to know about underground distribution methods and so forth, but it offers very little or no overhead line information helpful in the design, construction, and operation for present and future rural and other line development, and, it can be expected, in this country for some time to come that in overhead work there will be a general leaning towards underground construction and other practices in the way of protection and other requirements—a clearly distinctive dividing line should be maintained.

It is not exaggerating to say that *the* two distribution systems of the future will be the single-phase and the three-phase 4 wire. The latter system, either for *star-star* or *delta-star* (usually the former) 4-wire secondary in each case, is sure to be very widely used in every part of this and other countries. For this country the so-called "grid" and unification of systems will bring about its extensive adoption, and in view of this possibility, it is the system of distribution given preference herein. The author's experience of this system by overhead mains through the streets of a city[1] started twenty-four years ago. At that time the system consisted of three-phase 3-wire primary feeders and three-phase 4-wire secondary distribution mains. All feeders, mains, and services were overhead and supported on wooden poles, wooden crossarms, and wooden pins. The incoming line voltage to the main sub-station was 66,000, and the line construction was the same, excepting pins; this voltage was stepped down for the primary feeders after passing through the main sub-station. The three-phase 4-wire distribution system started out as a secondary distribution, and at the time the author joined the city undertaking[2] as its assistant superintendent, the principal work consisted in changing over this original method because of much trouble from voltage regulation brought about by increasing load. The new system, for the most congested areas of the city, consisted in locating transformer banks at respective centres of distribution and tieing in the secondary mains from the respective transformer banks, each section being operated independently from any other section. Banks of transformers (each of the same capacity) were installed in vaults under the sidewalk so that in the event of a transformer failure the parallel groups automatically supplied the necessary load until another unit was installed. This system did not differ from the distribution system of to-day, except that it was not tied together as a complete network. Network protection other than fuses were not used. The system referred to above for this country will no doubt follow practically along the same lines, and the above-mentioned experience of long ago simply goes to show how the thread of events and practices are

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[1] Sacramento, capital of California, U.S.A.

[2] Up to that time little practical experience had been gained with overhead conductors carrying very heavy current (a.c.) at low voltage. In carrying very heavy current (a.c.) at low voltage it was found that great care must be exercised in order to have equal voltages, by having the conductors properly arranged so as to get rid of the unequal voltages.

An experience of this nature occurred on the three-phase 4-wire network, where a bank of transformers had been installed. Some fairly long lengths of 0·4 sq. in. copper cable had been run and spaced only a few inches apart, the neutral being on the outside. It was found that, with the load approximately balanced, there was an objectionable difference in the voltage between the conductor located the furthermost from the neutral conductor. At the time this drop in volts was noticed the effect of inductance was not in mind. On disconnecting the neutral conductor and allowing it to drop until it hung beneath the middle conductor, the difference in volts drop disappeared at once, and, when the neutral was swung over further and placed beneath the conductor indicating the drop in volts, the drop again disappeared. This made it clear that, even for short lines, the reactance and not the resistance determines the *number* of circuits and the total current per circuit to satisfy best operation, etc.

interwoven, and little is new in this direction from that of a quarter of a century ago.

In comparing any system, such as the primary voltage for the feeders, it is of some interest to take into account certain relative advantages, such as relative weight of conductors, relative drop and loss, relative kVA capacity, relative area which can be served, assuming for each condition relations conforming with good practice, and for the same length, load, etc. Taking only the three best-known alternating current systems, viz. (A) the single-phase, (B) the three-phase 3-wire, and (C) the three-phase 4-wire, we find the relations to be approximately as follows for the primary voltages (respectively) likely to be employed for the feeders:

System Advantages.

Conditions.	(A).	(B).	(C).	(D).[1]
Relative weight of conductors, for same length, load, and power loss	1·0	0·75	0·33	0·188
Relative power loss on the line, for same length, load, and size of conductor . . .	1·0	0·50	0·165	0·125
Relative voltage drop in per cent., for same length, load, and size of conductor . .	10%	5%	1·66%	1·25%
Relative capacity, for same length, power loss, and size of conductor	1·0%	1·732%	5·23%	6·93%
Relative area which can be served, for same length, power loss, and weight of conductor	1·0%	1·78%	9·0%	16%

[1] (D) Double the voltage of (B); note that the weight is ¼, power loss is ¼, voltage drop is ¼, relative capacity is 4 times, and relative supply area served is 9 times that of (B).

The amount of copper required to transmit power by any given system (the three-phase system, for instance) with a given percentage power loss, or a given percentage voltage in ohmic resistance, varies directly with the amount of power, directly as the square of the distance, and inversely as the square of the voltage used. The area of the conductors for supplying power with a given percentage voltage drop or loss varies directly with the amount of power, directly with the distance, and inversely as the square of the voltage. If the percentage loss in the line is not fixed, but if the area of the conductor is proportional to make the annual expenditures for lost power plus interest plus depreciation and taxes on the conductor a minimum, then the weight of the conductor required varies directly with the amount of power, directly as the first power of the distance, and inversely as the first power of the voltage used. With the conductors proportioned for minimum annual expenditures, the area of the conductors varies directly with the amount of power and inversely as the voltage, and for a given voltage is independent of the distance. For two feeders of the same length supplying the same amount of power *at different voltages* and with the same power loss for both feeders, the area and weight of the conductors will vary inversely as the square of the voltage, *i.e.* as E^2.

Experience shows that an economical distribution consists in having a reasonable primary distribution voltage to start with, and for three-phase work, with feeders usually balanced as nearly as practicable, this can be obtained by dividing the service area into more or less uniform load sections for each feeder. The secondary mains for lighting would more generally consist of conductors of uniform size at all or most points, and operate on a single-phase 3-wire basis with neutral earthed. Where practicable, the main would be run longitudinally along the streets, roads, or *alleys*, and at intervals, cross-ties installed over cross-streets between the longitudinal runs—thus forming a "grid" network. For ultimate loading density, a maximum size of secondary grid could be extended considerably. "Insulating" circuit-breakers where desired could be placed in the secondary mains around the edges of each grid to separate it from adjoining networks, if any, except that no circuit-breakers are placed in the neutral network.

The general plan of operation would be to keep the bus-bar voltage constant at the sub-station and to regulate the various single-phase lighting feeders with regulators by which the voltage can be raised or lowered a desired percentage (between 10 per cent. range). In the primary distributing circuits, fuses and/or switches would be used at the transformer terminals only, and automatic circuit-breakers provided on feeders at the sub-station or stations. Time limits would not be placed on automatic circuit-breakers at sub-stations, but a time-limit device would be used on those at generating stations, so as to give the circuit-breaker on any feeder time to act before that at the generating station could open, and so prevent the opening of the station circuit-breaker in case of a heavy short-circuit on one feeder. The practice of this country would follow along the lines of underground methods, *i.e.* general use of pilot-wire schemes in preference to all others.

A single-phase primary grid consisting of bare or weatherproof conductor may, in some cases, be installed parallel to the secondary main (which latter can be likened to a *bus*) as to both location and area, and the secondary main neutral can be used with advantage as a primary neutral from the earthed side of the transformer to the feeding-point in the centre of the grid; for this country it is doubtful if this practice would be allowed. Branches from the neutral feeder would in such cases follow each single-phase branch, and tap the neutral grid at the same point where the primary grid is tapped. Additional taps may also be made from the neutral feeder conductor to various points in the neutral grid when necessary, as determined by neutral current tests to be best. This is but one of the various methods which may (or may not) be followed universally. The author firmly believes that the future distribution system will operate with a common earth neutral for primary and secondary, which practice will ultimately make for better operation, greater safety, lower construction costs, etc. It is therefore apparent that the author makes no apology for proposing the system given in figs. 6 and 32B (see following pages).

Primary voltage is generally controlled from the sub-station regulator for all drops up to the feeding-point in the grid, the total of which is added to the drop in distribution transformers as well as the drop in the consumer's services. The voltage drop in the primary grid from the feeding-point to the transformers, plus the voltage drop in the secondary grid from the transformers to the service pole, will vary at different service points, and the sum of these should be kept within a minimum range in order to keep within the maximum *permissible* voltage drop (see p. 57).

The full scope of advantages of the three-phase 4-wire system depends somewhat on the neutral, *i.e.* when and where it is earthed, and the method used for earthing it; this applies to all earthed neutral systems. The points and methods for earthing the neutral are several; we may

Earth at the supply end only (also see p. 216).

Earth at the supply end and at other convenient points.

Use a common earthed neutral for both primary and secondary lines; and

The neutral conductor should be supported on the same or adjacent crossarm with the corresponding phase conductor.

The length and load of a single-phase conductor should not be increased beyond a limiting distance that is reasonably practicable in the provision of good service. Also

Single-phase loads should be so connected that phase balance will be obtained with relatively short distances, and, preferably, these phase loads be supplied from transformers connected so that some part of the system has a *delta* connection (see fig. 32; also Table XLI.).

Use of the overhead ground (earth) wire and/*or* a continuous earthed guard wire as the neutral conductor, etc. Providing independent earths for transformers and lightning arresters (see pp. 198 and 216).

The method of earthing the neutral generally accepted throughout the world is that of earthing at the supply end of the system.

In fig. 6 and fig. 32B the author has shown a three-phase 4-wire system, but the proposal is for any type of circuit, line construction, and/or system, whether of wood, steel, or reinforced-concrete, etc., and for d.c., or a.c. single or polyphase systems possessing a natural or artificial neutral return; in the text, the wood support and the three-phase 4-wire system are given preference for the various reasons mentioned. The two-phase (or quarter-phase) interconnected [1] system is the next best, and, as distinct from the universal practice up to the present time, the author proposes the use of a continuous earth guard wire or an overhead earth (ground) wire to be used as the neutral return conductor, as well as for protective purposes both external and internal. Several important advantages have been mentioned in Chapter I. (see pp. 15–25), but the following will further substantiate the practical, economical, and protective benefits and improvements of this proposed system of distribution and transmission.

In the first place, let it be understood that it is definitely established and universally recognised that earthing will reduce costs and will tend towards greater safety in operation. Further, it is becoming more generally understood that multiple earthing is very necessary for both primary and secondary, and, without question, future practice will be that of using an earthed system common to both primary and secondary circuits.

As regards the three-phase system it is apparent that, when the load on the primary side of a 3-wire line has increased to a certain point, the simplest way to increase the line kVA capacity is that of changing from *delta* to *star*, and carrying a fourth conductor throughout the primary network or along a large part of it; the fourth conductor could be the overhead ground wire as proposed herein. Also, as regards the neutral itself, there is no reason why the primary neutral should not have multiple earths just the same as the secondary; as a matter of fact, underground

[1] This consists of two single-phase windings connected together at their middle points, forming a 4- or 5-wire system.

construction usually provides for earthing of the primary neutral at most manholes. Undoubtedly, the more earths installed the more effective the earthing will be; that is to say, the closer together the neutral earths are placed, the smaller will be the voltage gradient in any definite distance.

The question of to-day is not that of obtaining individual earths of low-impedance, it is one of obtaining a well-distributed low-impedance earth that will approach an *equi-potential* (not an equi-distant) area, and thereby avoid a high-voltage gradient when heavy currents flow to earth.

Earthing the neutral at the sub-station or the supply end *only* is likely to prove dangerous practice, as there is no indication at the supply end when the neutral on the line breaks; the circuit would not trip out and the fallen neutral conductor may produce a voltage to earth equal to that of the phase conductors, and may cause breakdowns in other ways and be a great hazard to apparatus and life. The safest solution is to earth at definite intervals out on the line, to reduce the neutral-to-earth potential at all points. Moreover, a broken phase conductor under these conditions may not indicate an abnormal condition at the supply end, nor trip the switches, but the hazard of dangerous voltage is present, due to earthing the neutral at the supply end only. Earthing the neutral along the line at equi-impedance intervals has the effect of safely earthing the fallen phase conductor, etc. and either indicating an unbalance or tripping the circuit.

The neutral conductor should not be of less size than 50 per cent. of the phase conductor; preferably, it should be larger than 50 per cent. The size is not required for normal operating current, moreover; the proper size means that balancing current in the neutral will travel the shortest possible distance. Its position in relation with the phase conductors along the whole line is also important (see footnote, p. 193, also p. 216).

In order to prevent the possible flow of current at the higher harmonics, the neutral point of three-phase *star-star*-connected transformers can be kept isolated from the overhead neutral conductor system (see p. 216).

At the supply end or sub-station *it is universal practice* to use a common earthing system, *i.e.* one general earth for the lightning arresters, transformers, neutral return, etc.; this is done for greater security, etc.

When several circuits are strung on the same pole line, one neutral conductor can sometimes be used for all the circuits, thus reducing costs in copper, crossarms, etc. and, where circumstances permit, the neutral may be converted into a "grid" system with all neutrals interconnected. The primary neutral and the neutral of secondary circuit or circuits using multiple earths on a pole line can, sometimes, with many advantages, be used to form one common earth for both systems. The advantages are, less possibility of high-earth resistance, better earth for lightning arresters, etc.

The advantage of a common multiple earthing system is that a resultant minimum earth resistance is obtained which can be taken advantage of for all earthing purposes, and, it provides a distributed earth which is of great importance in the reduction of potential gradients.

Actually what we desire for all lines is some simple and reliable means for giving the best and most lasting protection of the line insulators, the line in general, and the terminal apparatus from dangerous pressure rises. The most efficient and most economical and satisfactory means is the adoption of the right system in the first place, and the installation of a neutral earthed conductor used as an overhead earth (ground) wire or continuous earth guard wire. For the protection of a *line* and *system* from practically *all* external high pressures of the class looked upon as dangerous pressure rises, the continuous earth (ground) wire, combined with and forming part of the system neutral, will give better results than any other known single or group of devices or means; that is to say, it will, in the most efficient manner:

> Provide that intensity of over-voltages be considerably reduced. Give protection from direct strokes of lightning.
>
> Reduce the voltage electro-magnetically and electrostatically induced in the line conductors.
>
> Provide an effective damping on any disturbance or wave travelling along the line by its action as a short-circuit secondary.
>
> Give protection from static over-potential.
>
> Offer the most *preventative* means yet devised, and will lessen the duty of and danger to lightning arresters and other curative devices.
>
> Give protection from arcing earths.
>
> And, in general, prevent all types of dangerous pressure rises from external causes entering lines; for those entering, it will prevent them from travelling far along the line and will, commencing at their point of entry, dissipate the dangerous effects.

> Line insulation is rarely weakened by normal operating conditions; of course dirt and dust and age leave their effects, but the weak spots will be weakened or completely broken down by the external high-pressure rises mentioned above, which are always of the very high frequency type and are from line or phase to earth. We therefore see, as a result of these natural conditions, the value of the proposed type of *insulated* construction (fig. 6). This refers in particular to retaining the insulation of the wood support and using the system proposed; in fact, the question is far more important than can be gleaned at first sight.

Further, on an efficiently earthed overhead system (such as shown in fig. 6) most lightning disturbances which would reach the station over such an earthed overhead system should never be greater, but rather very much less, than those entering a station over the phase-conductors, which may or may not be discharged into the lightning arrester earths at the station—these earths being invariably connected to the common earthing system of the station. For the *continuous earth guard wire* they would rarely, if ever, be as great, hence the advantage of this method and position, which also offers other advantages for the line and system. Therefore, is it not logical and proper to use the overhead earth (ground) wire or the continuous earth guard wire (as the case may be) as part of the electric circuit? If no ill effects are experienced from the connection of lightning arrester earths over the phase conductors to the main station or supply end earth, certainly none can be expected from connecting the overhead earth (ground) wire or the continuous earth guard wire to an *independently* earthed (and much better earthed) system or/*and* to the same earthed system at the station or transforming centre, etc. which surely is better and is more reliable and effective. The proposed method will improve the station earth, provide better relay action, reduce the hazard to life and apparatus, reduce the materials and cost of the line, give the *lowest* maximum and most stable voltage above earth, provide better operating conditions, and give a better and cheaper system in every way.

Quite apart from the distribution system adopted, the secondary system will invariably be subjected to hazards from high-voltage transformer windings and/or from high-voltage line crosses, and the best and safest practice would be to

> *Earth all low-voltage lines*, as earthing to a large extent decreases the danger of fatal shocks in case the circuit becomes

crossed with one of high voltage; this is because the normal voltage to earth is in itself relatively safe.

Earth or *insulate medium-voltage lines,* as earthing does not sufficiently decrease the danger of fatal shocks in case the circuit becomes crossed with one of higher voltage; certainly the normal voltage itself is dangerous.

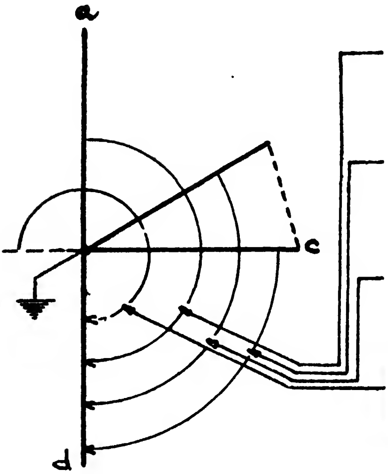
Earth high-voltage and extra-high-voltage lines. Obviously for such voltages, earthing or insulating cannot in any way change the danger of shock. Earthing of such circuits is intended for the purpose of decreasing hazards and increasing reliability, decreasing or limiting the voltage stress on the whole system, and decreasing the cost of line, etc.; the factor of safety is higher for a system with earthed neutral than one with isolated neutral.

From these findings, and for all voltage lines, the earthed neutral system is certainly the safest (also see p. 23).

There is sometimes substantial advantage and economy in combining the primary and secondary neutrals in one conductor in order to ensure both functions, as mentioned above. It is, of course, essential that the neutral be effectively earthed. This method would seem to be essential certainly for rural single-phase lighting branches and pole transformer service. With this method the two outer conductors of the secondary form an additional return path in parallel with the neutral, and the primary single-phase load current divides nearly in the ratio of copper cross-section. The return path through the neutral network is of a complex nature, but from tests from various systems it is found that at least 65 per cent. returns through the neutral on the same pole route with the primary. Each primary district can be served by a three-phase main which could tap into a ring feeder, the ring being sectionalised between adjacent taps and normally left open, but capable of being closed in emergencies. The centre load area of each feeder district would be divided into single-phase sub-districts, so distributed among phases as to minimise the unbalanced load current in the neutral along any given three-phase route.

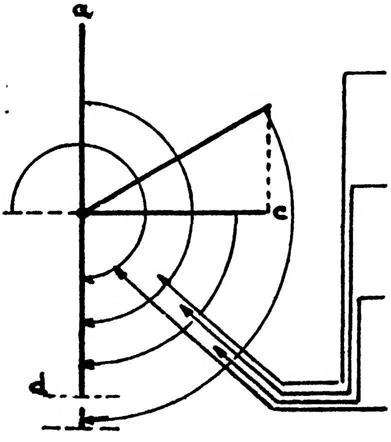
It would be the general practice in certain districts to carry the three-phase primary fairly well out to the end or near the end of most branch-lines in order to obtain the full advantage of three-phase light and/or power service and to ensure a more balanced load. On the other hand, it may be uneconomical to string a three-phase 4-wire service main; load conditions and character of load usually decide the requirements.

Showing True Comparison, with the Direct Current System, for Maximum Voltage above Earth and for Maximum Voltage between Conductors.



System.	For the same Maximum Voltage above Earth, and taking E = 100 Volts between any Conductor and Earth.
	(*Relative voltage danger*) *Maximum Voltage between Conductors* =
Single-phase	$2E\sqrt{2}=283$
Two - phase 3-wire .	$\sqrt{2}E\sqrt{2}=200$
Three-phase	$\sqrt{3}E\sqrt{2}=245$
Two-phase .	$2E\sqrt{2}=283$

ad = single-phase = one phase of the two-phase system, or two legs of a *quarter*-phase system.



System.	For the Same Maximum Voltage between Conductors—*Relative Amount of Copper Required.*
Single-phase	100% ; that is, $2/\cos^2\phi$
Two - phase 3-wire .	145% ; „ $2{\cdot}92/\cos^2\phi$
Three-phase	75% ; „ $1{\cdot}5/\cos^2\phi$
Two-phase .	100% ; „ $2/\cos^2\phi$

Note.—These voltage and phase diagrams are drawn to scale for purpose of visualising the true relations.

A rural feeder scheme may involve the use of a secondary circuit-breaker, which opens reverse power, and one that is reclosed either by hand or automatically; such a scheme should be backed by fuses. The automatic reclosing breaker, after tripping under reverse power from the network, should reclose in case the voltage on the network side is lower than on the transformer side. The feeder and its transformer should be disconnected from the system in the event of any fault.

Transformers may be completely isolated from feeder sections, or may be solidly connected to them and operate as respective units with them; this latter is generally the only expedient. Differential protection can, as desired, be employed across each transformer installation.

The use of a strictly radial primary feeder system may effect a saving in linear yards of primary line, but for maximum economy it may be necessary to taper off the conductor size in order to avoid excessive voltage gradient between feeding-point and the outer edge of service area with heavy load densities. The added cost of the larger conductor, together with the cost of putting up conductors to keep up the load growth, is more likely to offset the cost of the added linear yards of primary in the grid form of feeder. The use of a secondary network (not always obtainable in rural districts) effects great economy in transformers, and, where good construction is employed, experience shows that service conditions have been much improved.

For maximum service continuity it may be necessary to parallel and/or interlace the different feeders, and this may take several forms for the different schemes used. The degree and kind of interlacing will affect the capacity of feeders of transformers as well as the characteristics of the system.

Each of the sections of an interconnected secondary network should be so designed that respective transformer installations are at the approximate centre of the load on the section, preferably so located that the current is distributed in a number of directions. Thus, if there is a group of properly designed secondary sections (possible in urban areas), they can be interconnected with advantage to form a network for parallel operation.

In the event of failure of any transformer on the network, its load should be taken up by adjacent transformers if continuity of service is to be maintained; and this is where a danger lies if the network transformers are not properly proportioned as to sizes and do not have proper protective equipment. On this particular point it is evident that:

> Impedance in the circuits between paralleled transformers may cause heavy cross-currents, etc., hence transformer distant spacings may present a danger and a loss.
>
> The more transformers there are in parallel, the smaller proportionate overload each will bear when any one unit fails; and that
>
> .All units feeding into any interconnected network should be of approximately the same rating, otherwise a failure of any larger unit will disproportionately overload the smaller one adjacent thereto.

The most economical practice in the long run is to have only a few standard-sized units, and to run moderately heavy secondary mains to permit taking on additional load as the district develops, by simply adding transformer units at intermediate points on the existing mains. It is bad practice to install small secondary mains and small transformers, for the cost of continually increasing their size as new load comes on means a relatively heavier ultimate investment, rapid depreciation of materials used, loss of revenue, etc. To this end, *pole sizes* in the initial stage of developing an area should not be overlooked; also, the best use of transformer types should not be overloaded, *i.e.* single-phase units and polyphase units.

The loop-feeder scheme with sectionalising circuit-breakers on the primary feeder side can be operated with an automatic circuit-breaker with fuses on the low-pressure side of the transformers. As the loop is sectionalised, in the event of trouble only a section of the feeder is disconnected from the system. In view of its simplicity and reliable operation, the balance pilot-wire protection methods for this scheme and this country seem to be preferable to the reverse-power and other relay methods of protection, but they should not be instituted regardless of *all* factors.

Transformers supplying lighting service may (or may not) be connected in parallel on their secondary side; but where they are not so connected, they should be connected consecutively across the various phases of the primary feeder, with an endeavour to maintain as nearly as possible or practicable a balanced load on the three-phases locally, *as well as* the total at the sub-station.

In the design of any distribution *secondary* system the voltage at the consumer's services (terminals) is of first importance. The voltage is limited by law, as is also the voltage drop. The safe maximum voltage of the secondary supply is relatively high; in fact so high as to affect the life hazard far more (when comparing relative numbers of consumers) than the possibility of a broken primary feeder, which is far too speculative and is well out of the way under normal conditions; that is, for this country, the voltage at the consumer's terminals would normally be 400/230 volts, or a d.c. equivalent of $\sqrt{2} \times 400 = 566$ volts or/and $\sqrt{2} \times 230 = 325$ volts at the lamps for the latter case (a dangerous voltage), and motor installations for the former case. Interlinked with the life hazard is the fire hazard—both hazards are greatly diminished by having the neutral point of the system solidly earthed. As distinct from this system, in times of line trouble the normally non-earthed system may be earthed on any phase conductor, or certain line conductors may cross, and under these conditions the linemen clearing the trouble may be exposed to much higher maximum voltages because of the many possible combinations of earths and crosses and relatively greater dangers of a non-earthed system.

The secondary system protection when considered in the form of a grid is divided into:

> Protection based on faults in the mains, clearing themselves by burning clear;
>
> Protection based upon fusing the mains, or blowing fuses, to disconnect the main in trouble—this being the common method employed.

The single-phase 3-wire system can be taken as the equivalent of two 2-wire systems combined, so that one conductor serves as one side of each of the two systems, just as in the d.c. 3-wire system. If the load is exactly balanced between the two systems, the neutral conductor carries no current, and the system acts as a 2-wire system at twice the voltage of the component systems, with each unit of load of one component system in series with a similar unit of the other system. If the neutral is not balanced, the neutral conductor carries a current equal to the difference between the currents in the outside conductors. For a balanced system the power loss and volts drop are computed in the same way as for a 2-wire line consisting of the outside conductors, neglecting the neutral. For a three-phase 4-wire system conditions of unbalance load are more complex than the single-phase 3-wire system.

It is obvious that, with time, sections of a distribution system develop to such an extent that, owing to the resulting poor regulation from growth of load, the only remaining solution for a single-phase line is to convert to the three-phase 4-wire system; this change being necessary for the purpose of not only improving the service, but also for increasing the economical radius of distribution.

In changing over from *delta* to *star* with earthed neutral (to the three-phase 4-wire system), a number of weak points are likely to show up at the time of change-over, but once these are cleared the operation is as reliable as any system, such as the *delta* system with isolated neutral. There are advantages in having a fault show up at once by causing a short-circuit, in preference to a number of weak earths which may show up at once or show up at the wrong time, *i.e.* during the worst weather and/or under heavy load.

In the three-phase 4-wire distribution system, which is a symmetrical polyphase system, the transformer or transformers, for polyphase use, are ordinarily connected in *star* or *delta* on the primary side and *star* or *delta* on the secondary side; *star-star* is the most economical (see Table II.); *delta* connection on the secondary side is very rarely employed for 4-wire distribution, and it is an unsymmetrical polyphase system.

Since the line voltage in the three-phase 4-wire system is 1·732 times that of the three-phase 3-wire, the line current is proportionally less, and the line drop is directly proportional to the line current; it therefore follows that the size of conductor required for the same kVA load and with the same permissible loss is one-third (0·333) of that required for the 3-wire three-phase; it is therefore admirably suited to primary distribution. It also follows that if a 3-wire three-phase line is converted into a 4-wire three-phase line, the kVA capacity of the circuit is threefold, which is a better reason for using it in primary distribution. Also, if two single-phase circuits are combined into one 4-wire three-phase circuit, the kVA capacity of the latter is three times that of the two single-phase circuits combined.

The earth (the ground itself) can be, and sometimes is, used for the neutral as a return, but a fourth conductor is always desirable and represents good practice. Nevertheless, emergency cases do arise, and for such cases have been applied by the author in certain foreign countries, where the ground itself was used as the return or fourth conductor. Fig. 32 is the preferred method.

One of the advantages of three-phase 4-wire distribution is its successful application for both power and lighting purposes regardless of load balance. If a single-phase feeder regulator is installed in one phase, it can be adjusted to give a constant voltage at any point on the line regardless of the load on the other phases. A three-phase 4-wire circuit can be used for supplying all the current

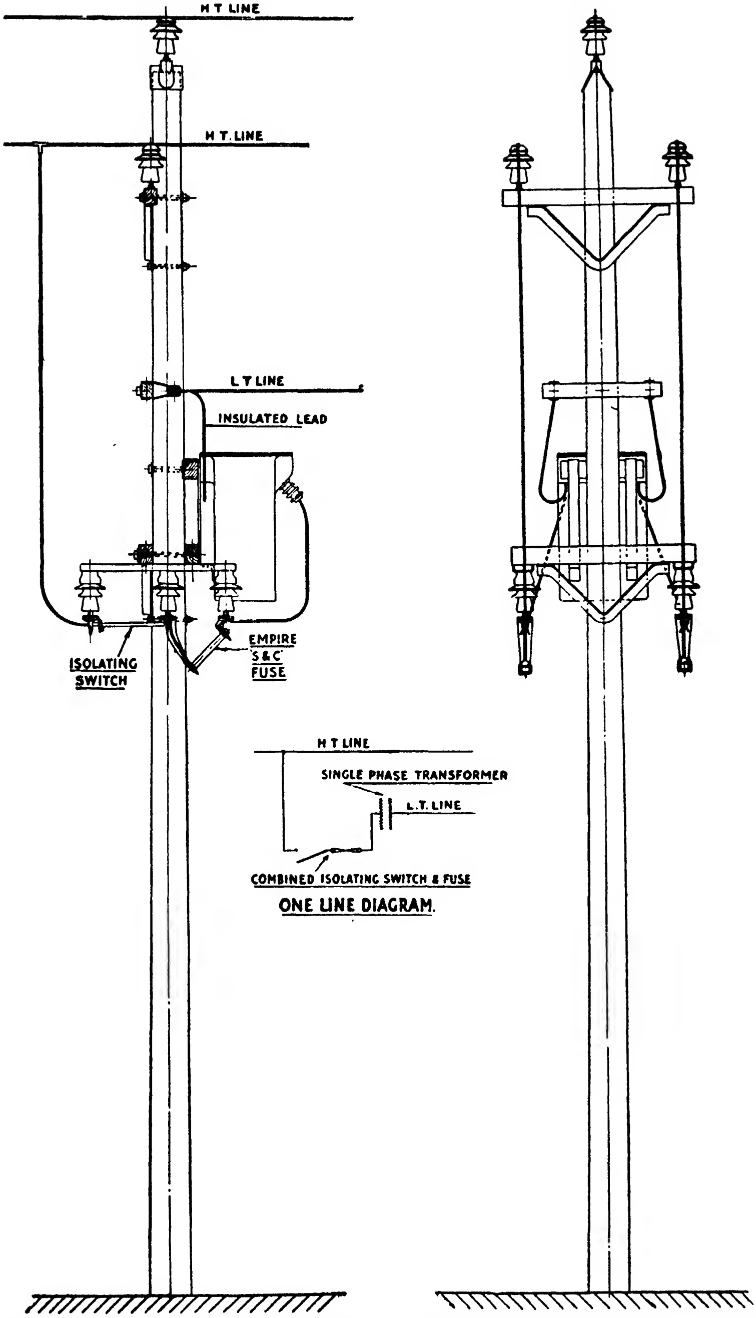


FIG. 31.—Showing good type of distribution-transformer pole installation. (*Henley.*)

for an area, whether it is used for lighting, power, or heating, and the necessity of duplicate or multiple or paralleling of circuits as well as investment costs are thereby rendered submittive, and the method of supplying the load tends to increase the load factor on the circuits as well as the diversity.

If the circuit district is fed by single-phase mains, it may be more desirable to divide it into a number of divisions, each fed by a single-phase feeder from the star (1·732 voltage) feeding-point. With this arrangement, single-phase distribution is maintained and operated just as on the phase to neutral voltage (1·0 voltage) system, and the change from one system to the other is thus greatly facilitated. Each single-phase feeder is connected across a different phase, the endeavour being to keep the loads as equally balanced as practicable.

If a district is fed by three-phase mains, it may have a principal main with branches, which are either single-phase or three-phase, depending upon the density and/or the connected load and the load size in units. If possible, this principal main should be laid out to connect with the principal main or mains of adjacent circuits, and full advantages can then be obtained whenever the load requires rearrangement of the circuits.

If the neutral conductor of the three-phase 4-wire should break, which is possible in overhead work, and a serious condition to study, an unbalanced load on the phases may result, and this may cause an unbalance in voltage sufficiently high to overstress lamps in the circuit at the time. This is caused by the change of current in both primary and secondary windings of the transformer, and if two phases are heavily loaded and one phase is almost without load, the difference in reactance in the primary may cause the neutral point of the circuit to be moved out of centre. The transformer winding on the loaded phase would then be practically in series between the phase conductors, and would deliver a secondary voltage nearly double that under normal conditions; the transformer winding on the phase carrying very little load would have a voltage of about double impressed upon the primary, and the secondary would probably be very much higher voltage than under normal operating conditions. Such a condition with good line practice is unlikely, but one of the surest ways to overcome such a hazard is not only to earth the neutral at the generating or main sub-station or the distributing centre (as the case may be), but connect the earthed neutral of different circuits if possible, or, failing this, earth it at other most effective and convenient points on the distribution. In this way one or another of the connections would serve as a path in parallel with the neutral conductor, and the earth would take care of the unbalanced load and prevent sufficient distortion from the broken neutral doing any damage. The neutral conductor may have a switch or a link, but never a fuse in its circuit (see also page 20).

Where three-phase 3-wire power circuits are strung, sometimes it may be found advisable to run a fourth conductor to provide for *open-star* operation of a transformer bank, or wherever it may be desirable, to take an emergency single-phase lighting connection from the power circuit. Also, for line construction in general, where there are three-phase 3-wire circuits there should be satisfactory space available for the location of a fourth conductor on the pole. In fact, there are so many advantages in using the three-phase 4-wire primary feeder and three-phase 4-wire secondary main distribution that it will be very generally used in future (see fig. 32).

When a large area is to be supplied, the best voltage regulation is obtained by establishing distribution centres to which power is supplied direct by feeders, and from these power can be distributed to mains, thence to the consumers. Between these distribution centres and the supply sub-station no load is, as a general rule, taken off the feeders; hence the voltage at the distributing centre can be kept at a constant value, and the mains (or/and large consumers) can be supplied with better voltage regulation than would otherwise be possible. Pilot wires from the distribution centres may lead back to the station voltmeter, so that the operator in the station can keep the voltage at the distribution centres quite constant. In feeder systems provided with wires for regulating the voltage at the supply end, the voltage drop is not limited to the low value permissible for lighting mains; hence the conductors may, as desired, be proportioned for economy.

As a general rule, a single-phase feeder regulator for lighting circuits is used on each phase conductor; such a regulator would have the primary excited from a phase conductor to neutral, and the secondary in series with the phase conductor. If the load is unbalanced, current will flow through the neutral conductor, and a line-drop compensator and current transformer employed to provide compensation for drop on the neutral conductor. The regulator is placed in series with the phase conductor, and set to compensate for the drop along the line to the feeding-point. A compensator is installed in the neutrals of long radial circuits to compensate for the neutral drop in case of badly unbalanced loads. Regulation is improved by not connecting load to the feeders between the station and the centre of distribution;

sufficient copper should be provided to ensure good regulation to the distributing mains beyond the feeding-point.

The desirability of a careful balance of load on a three-phase 4-wire feeder is not so very important as many believe, because, with this system, the neutral conductor carries the unbalanced current, and the pressure can be regulated on all phases satisfactorily, practically *regardless* of balance. For a rural district it is usually necessary (because of initial cost) to start out with a single-phase feeder; this we can do without fear of poor regulation. We can start out single-phase and use one voltage regulator only and place all lighting load on that phase, and as more lighting load is added, another single-phase regulator and phase conductor can be installed; finally, the third phase can be loaded so that all the three phases are ultimately loaded. In practice this method of operating a three-phase 4-wire system has proved both economical and entirely satisfactory; a voltage-drop compensator is, of course, installed in the neutral conductor. It is sometimes stated that the three-phase 4-wire system is very poor in regulation as compared with the best of other systems—actually the opposite is the case. In fact, the method of operation outlined here should help to show the superiority in flexibility and extent of this system over all others (see p. 189). It is admirably suited to distribution in scattered districts where low first cost, difficulties in balancing loads, and good regulation are the criteria, and where the system, taken as a whole, can be put in piecemeal and require the least modification to complete the whole. And, apart from its advantages by using the indirect method, this system also permits feeders to be loaded more heavily than is possible when a load is distributed from a single centre.

For the three-phase 4-wire system, if it is required to keep the voltage drop as low as possible in case of unbalancing and also to provide for single-phase operation in case of a phase conductor breaking, the neutral conductor should, wherever possible, be of the same size as the line conductors (see Table XXXVIII.). From this view-point it is well to keep in mind that it may be better, and more economical in the long run, to deal with excessive voltage drop by additional copper than by depending too much on voltage regulators, and additional copper always offers advantages in other ways; on the other hand, it would be unwise to omit voltage compensator advantages for such cases. Earthing the neutral at one point is the law, but it is usually found that better and safer results are obtained by earthing the neutral at the station *and* at another desirable point (see also p. 197).

TABLE XXXVIII.

RELATIVE CONDUCTOR REQUIREMENTS FOR EQUAL kW DELIVERED, WHICH IS THE MORE PRACTICAL BASIS FOR COMPARISONS, ASSUMING $\cos \phi = 1{\cdot}0$.

Conditions.	Relative Total Conductor Weight, based on Voltage between Line (or Phase) Conductors.						
	D.c. or *A.c.*		*Two-phase*[2] 4-wire.	*Quarter-phase* 5-wire.	*Three-phase.*		
	2-wire.	3-wire.			3-wire.	4-wire.	4-wire.[1]
Equal percentage power loss	1·00	1·25	1·00	1·25	0·75	0·875	1·00
Equal percentage ohmic volts drop . . .	1·00	1·25	1·00	1·25	0·75	0·875	1·00
Relative economic size .	1·00	1·25	1·00	1·25	0·866	1·01	1·155
(Based on Voltage from Line (or Phase) Conductor to Earth.)							
Equal percentage ohmic volts drop . . .	1·00	0·313	1·00	0·282	0·75	0·292	0·333
Equal percentage power loss	1·00	0·313	1·00	0·282	0·75	0·292	0·333
Relative economic size .	1·00	0·625	1·00	0·563	0·866	0·583	0·666

[1] Neutral conductor is of the same size as the line (or phase) conductor, this being the more effective practice. In all other cases given in this table, the neutral conductor is based on it being 50 per cent. as large as one of the line (or phase) conductors.

[2] This two-phase 4-wire system does not carry a neutral conductor. For a.c. systems, unity power factor is assumed here. The *quarter*-phase 5-wire is an interconnected two-phase system.

The voltage drop between any two points on a distribution circuit is the difference in voltage between those points, or the voltage necessary to pass the current through the series impedance between those points. That is, it represents the difference between the maximum and minimum voltage, or difference between voltage at no load and at full load. Voltage drop is not equal numerically to impedance drop except when the impedance drop is *in phase* with the line voltage. Voltage drop is more commonly expressed by the approximate formula:

$$I(R \cos \phi + X \sin \phi) \text{ volts} \qquad \text{(see p. 104)}$$

where R = resistance of conductor in ohms between the two points considered;

X = reactance of conductor in ohms between the two points considered;

I = current in amperes;

$\cos \phi$ = power factor of the load;

Single-phase or polyphase regulators may be used, but the former practice is more general.

The total regulator capacity is given by

$$P\frac{e \text{ per cent.}}{100} \quad (\text{kVA})$$

where e per cent. = regulator rated percentage;

P = line load in kVA.

Thus, for a single-phase feeder with transformer ratio of 10 to 1, the voltage boost or buck is usually 10 per cent. and the total booster capacity, in percentage of total line load in kVA, is 10 per cent.; for a three-phase system with a three-phase transformer unit, connected *star* on primary side—for a 10 to 1 ratio—the percentage voltage boost and buck is 17·32 per cent., and the total booster capacity in per cent. of total line kVA is the same; and where three single-phase transformers of the same ratio (10 to 1) are used and connected in *star* on the primary, the voltage boost and buck is only 10 per cent., and the total booster capacity in per cent. of line kVA the same, but for a *delta* connection it is 17·32 per cent.

In certain emergency operations the methods available are fundamental. Taking a few cases and going back some twenty-five years, the author recalls certain methods of emergency operation (employable to-day and for all time), where, for instance, a phase conductor is broken or a transformer disabled, or where the cheapest safe construction is desired. In those days where the load was small, it was sometimes found necessary to string one conductor *only* for a single-phase service, and earth one side of the transformer giving (for long periods on end) supply to rural districts. For loads up to several hundred kVA it was sometimes found necessary to operate a three-phase circuit on two conductors for a polyphase motor service, using earth return on the primary and *open-delta* on the secondary. On the 66,000-volt system, loads of over 1000 kW were transmitted very long distances (sometimes 100 miles), using only two single-phase transformers *star*-connected on the primary with earthed neutral, and *open-delta* on the secondary; very often the consumers were none the wiser. Also, where one phase of a three-phase group of transformers supplying a three-phase 4-wire distribution was damaged, the remaining two single-phase units were operated to supply three-phase motor service of very large aggregate capacity; this latter emergency measure (see p. 214) also served where one-phase conductor was broken. These are useful substitutes for operating engineers and others, and where permitted by law, should prove helpful to tide over an emergency period.

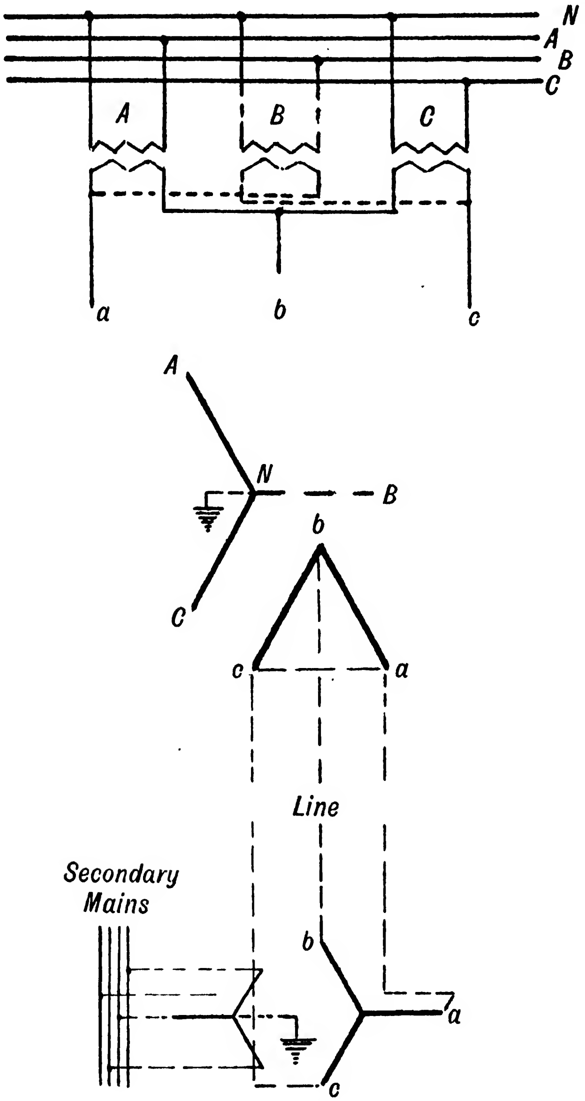


Fig. 32.—Showing method of obtaining three-phase supply from *star-delta* when one-phase transformer has failed.

To overcome most possible operating troubles the first thing is to start out with the right system, and where possible make use of emergency methods outlined above when other permissible

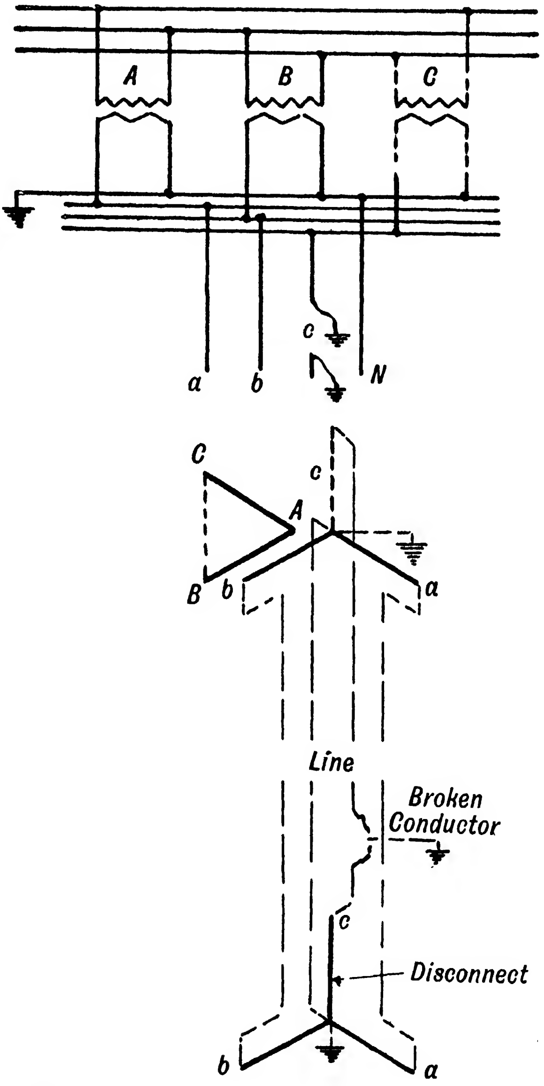


FIG. 32A.—Showing method of obtaining three-phase supply from a three-phase 4-wire system with *a broken phase conductor* and/or with *a disabled phase transformer.*

methods fail. In the layout of the distribution system itself, it is necessary:

To arrange emergency feed in case of a failure in a feeder, or on a section of a main, by providing for the transfer of load between circuits at various points; the transfer of load between circuits usually can be effected by pole-type disconnecting switches.

Where an outage of power service may cause serious inconvenience or possible loss of life, arrange for duplicate service to be taken either from a neighbouring power circuit or, if possible, run a lighting circuit where three-phase lighting mains exist.

Same as the last mentioned for power; the lighting service should take duplicate service from other lighting circuits or from single-phase or a power circuit.

For the purpose of isolating a defective portion of the circuit, to install pole-type disconnecting switches.

To arrange for an emergency circuit which may be fed from the same sub-station as a regular circuit, or where possible the circuit may come from an entirely different sub-station, thereby offering greater assurance of continuous service.

To provide emergency circuit by overlapping the mains of circuits from two different sub-stations and provide taps from both circuits, and arrange switching so that service can be transferred readily to either main; this has an additional advantage over the last-mentioned method in that it provides against a failure of an entire sub-station or main transformer bank or three-phase unit.

To have the neutral conductor of the same size as phase conductors, so as to provide for single-phase operation in case of emergency.

In order to protect all parts of the circuit against excessive voltage to earth, and to protect single-phase transformers for lighting against excessive voltage, to earth the neutral at a sufficient number of points along the line, or have the different neutrals tied together.

Provided that the neutrals of power banks of transformers, or polyphase units, are not tied in, the three-phase 4-wire system of distribution usually offers less likelihood of service interruptions to lighting loads than the three-phase 3-wire circuit, for, if one phase breaks down the other two phases and neutral are still able to supply their respective single-phase loads with but little or no effect occasioned from the failure of the other phase transformer.

In so far as the question of lightning protection for pole-type transformers is concerned, where single-phase transformers are used, it is desirable in most countries to connect an arrester for full line-voltage on the phase conductor, and a spark-gap of low voltage on the neutral conductor. On power transformers it is desirable to connect arresters for full line-voltage on each of the phase conductors and install a low-voltage spark-gap on the neutral conductor. By earthing the neutral of the circuits both at the supply end and at the feeding points, some lightning protection can be obtained. In this country, protection from lightning is expected from the use of a short length of cable. For good earths, earth the lightning arresters and transformers independently of the system general earth.

Automatic transformer protection is provided either by the balanced method or by reverse power relays on the low-voltage side combined with overload and/or earth leakage protection on the high-voltage side; also pilot-wire schemes.

The different transformer connections likely to be used on distribution service, and the relative percentage kVA capacities of single-phase groups, are:

TABLE XXXIX.

RELATIVE TRANSFORMER RATING FOR DIFFERENT SYSTEMS.

Method of Connection employed.	Required Single-phase Rating.	Number of Single-phase Transformers employed.
Star-star	6×100 =600	Six
Delta-star	6×100 =600	Six
Delta-delta	6×100 =600	Six
Delta-" V "	5× 80 =400	Five
" V "-" V "	4×86·6=347	Four
" T "-" T "	4×86·6=347	Four
Delta	3×100 =300	Three
Star	3×100 =300	Three
" V "	2×86·6=173	Two
" T "	2×86·6=173	Two

In preference to adding reactance study the addition of reserve transformer kVA capacity, which is more effective and permits better voltage regulation owing to the decreased impedance. For overhead distribution lines increased impedance is not nearly so important as for underground construction. The choice of the correct transformer reactance depends on the size, length, and arrangement of the secondary distribution, spacing and size of distribution transformers, type of load and its distribution, etc.

High reactance is desirable from the view-point of interrupting

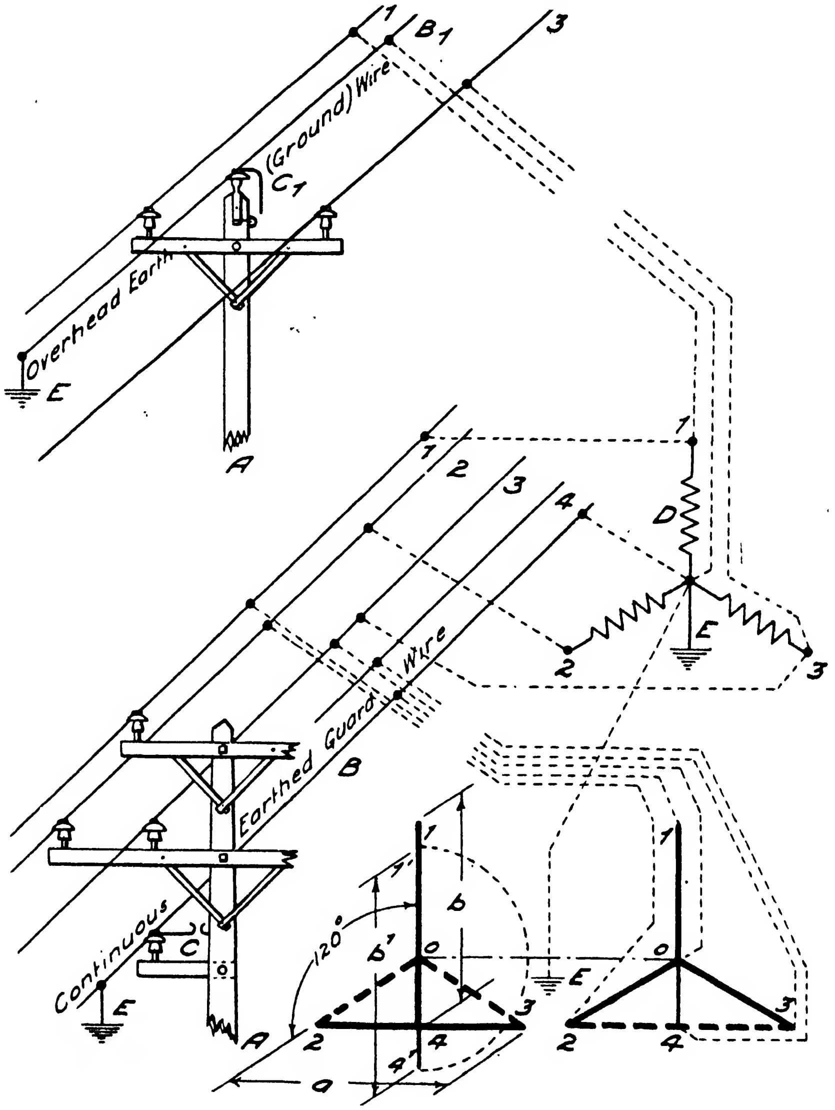


FIG. 32B.—Distribution system with proposed modification representing the three-phase 4-wire. Also for supply or transformation of three-phase, 3- or 4-wire, and/or two-phase 4- or 5-wire symmetrical relations and a common return or neutral for both systems.

Note.—The author recognises that such a practice of earthing as shown here is, as yet, not permissible in this country.

an arc-fault. It is also desirable from the point of capacity since the current will be supplied from more transformers, thus making more transformer kVA capacity available to carry a short-circuit current. Where distribution transformers are operated in parallel and situated some distance apart, respectively, the impedance of the circuits plays an important part on economical operation, cross currents, voltage drop, etc.

TABLE XL.

RELATIVE MAXIMUM VOLTAGE STRESS FOR THE MOST USEFUL THREE-PHASE SYSTEMS, WITH EARTHED NEUTRAL.

(By the *Indirect* (Multi-transformation) Method, see p. 186.)

<table>
<tr><th rowspan="3">Transformer Connections.</th><th colspan="5">Relative Maximum Voltage.</th></tr>
<tr><th colspan="2">On Phase Unit.</th><th colspan="2">Between Phases.</th><th rowspan="2">To Earth.</th></tr>
<tr><th>Step-up</th><th>Step-down.</th><th>h.p.</th><th>l.p.</th></tr>
<tr><td><i>Delta</i>-“ <i>Y</i> ” to “ <i>Y</i> ”-“ <i>Y</i> ”</td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td><i>Delta</i>-“ <i>Y</i> ” to <i>Delta</i>-“ <i>Y</i> ”</td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td>† <i>Delta</i>-“ <i>Y</i> ” to “ <i>Y</i> ”-<i>delta</i></td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td>† “ <i>Y</i> ”-<i>delta</i> to “ <i>Y</i> ”-“ <i>Y</i> ”</td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td>† “ <i>Y</i> ”-“ V ” to “ <i>Y</i> ”-“ <i>Y</i> ”</td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td>† “ <i>Y</i> ”-<i>delta</i> to “ <i>Y</i> ”-<i>delta</i></td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td><i>Delta</i>-<i>delta</i> to “ <i>Y</i> ”-<i>delta</i></td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td>“ <i>V</i> ”-“ <i>V</i> ” to “ <i>Y</i> ” “ <i>V</i> ”</td><td>1·000</td><td>1·000</td><td>1·000</td><td>1·000</td><td>0·577</td></tr>
<tr><td colspan="6">(By the <i>Direct</i> (Single-transformation) Method, see p. 186.)</td></tr>
<tr><td>† “ <i>Y</i> ” to “ <i>Y</i> ”</td><td colspan="2">1·000
1·732</td><td colspan="2">1·000
1·000</td><td>0·577
1·000</td></tr>
<tr><td>† “ <i>Y</i> ” to <i>Delta</i></td><td colspan="2">1·000</td><td colspan="2">1·000</td><td>1·000</td></tr>
<tr><td>† “ <i>Y</i> ” to “ <i>V</i> ”</td><td colspan="2">1·000</td><td colspan="2">1·000</td><td>1·000</td></tr>
<tr><td><i>Delta</i> to “ <i>Y</i> ”</td><td colspan="2">1·000</td><td colspan="2">1·000</td><td>1·000</td></tr>
<tr><td>“ V ” to “ <i>Y</i> ”</td><td colspan="2">1·000</td><td colspan="2">1·000</td><td>1·000</td></tr>
<tr><td><i>Delta</i> to <i>Delta</i></td><td colspan="2">1·000</td><td colspan="2">1·000</td><td>1·000</td></tr>
<tr><td>“ <i>V</i> ” to “ <i>V</i> ”</td><td colspan="2">1·000</td><td colspan="2">1·000</td><td>1·000</td></tr>
<tr><td>“ <i>T</i> ” to “ <i>T</i> ”</td><td colspan="2">1·000</td><td colspan="2">1·000</td><td>1·000</td></tr>
</table>

Note.—The last three systems do not have “ neutral ” earthed; unearthed systems are subjected to a voltage to earth equal to 1·732 times the normal value. † Neutral point of generator also earthed.

CHAPTER VI.

ASPECTS OF DISTRIBUTION MAINTENANCE.

In contrast to transmission lines, distribution lines require much more watchfulness due to their relatively more dangerous locations and to the relatively greater handling to which they are subjected. It is during the winter months, or the period of severest weather, that particular vigilance must be exercised by the linemen.

Public highways are not suitable places in which to locate and run distribution lines and service connections. For primary supply to rural areas, always seek fields in preference to roads, and for residential areas seek alleys or back-plots in preference to streets, for they are not only safer because people do not ordinarily use back-plots and alleys to the same extent as front entrances and streets, but usually both sides of alleys can be served, thus avoiding two pole lines in a street or the crossing of streets with service connections.

Requirements of maintaining service have introduced the practice of looping or paralleling feeders on the same secondary side, and also paralleling a multiple of feeders on the same secondary network. In some cases alternate transformers are connected on different feeders providing maintenance of service on the network in case one feeder fails.

Proper maintenance should be established and periodical inspections made of poles, crossarms, pins, stays, etc. This is the surest way to guarantee full continuity of service.

Where the low-pressure secondary network is protected adequately by earthing, there can be little or no hazard from high-pressure crosses, accidental or intentional. A minimum impedance and ample current-carrying capacity should be maintained from the secondary distribution system to earth, and this is best effected by a continuous network for the secondary neutral covering the whole area served. Periodic tests of the impedance to earth should be made; these tests should be made during the dry periods.

A dangerous line will comprise one or more of the following: one with defective supports; insufficient accessibility and/or clearances between lines and conductors, above ground, from buildings, and working clearances; insufficient strength; insufficient protection; too great a tension; too high a resistance (or impedance) to earth; insufficient feeder protection; unreliable earth leakage relays; insufficient secondary protection; insufficient protection of communication circuits from high-pressure conductors, etc.

The " V " guard and certain forms of guard wires are often dangerous and unnecessary, and it is always better to apply means to prevent a conductor falling than to load up a support with devices to catch it on its way down. In all cases, prevention is better than cure. Either design and construct so that safety devices are not required, or provide *perfect* safety devices for the line—do one *or* the other. Adopt,

correctly apply, and think more of proper safety standards of construction and the best system, then there will exist little or no reason to put up so-called safety devices.

PREVENTION of accidents is more desirable than cure, and all lines should be designed and constructed to stand up to the work required of them, and any spare money (intended for guards and the like) would be more profitably spent in improving the line itself.

Climatic conditions affecting operations are of a varied character and demand every attention as already pointed out. It is only by a careful study of any given district that safe and proper loading conditions and the most correct design can be determined. The various climatic and atmospheric conditions to be encountered in operation, are:

Rapid temperature changes;
Coating of insulators with dirt or dust;
Insulator depreciation induced by high daily temperature ranges;
Deposit of soot and/or fog;
Very wide temperature changes;
Hazards increased by the arrangement of conductors, method of construction, etc;
Heavy or long steady rains;
Lightning storms;
High winds and/or ice loadings.

Thus we find, owing to climatic and atmospheric conditions and certain kinds of construction, that worse dangers are encountered in insulation than mechanical strength, and this is applicable to all voltage lines. It has been shown that the best operating conditions are obtained with wood poles free from earthed wires in contact with them; for such lines the construction costs are the lowest and operating conditions the best. Where lightning storms are practically non-existent, which are the usual conditions prevailing in this country, this practice is especially recommended for lines in general and for all voltages up to the highest in use, or likely to be used in future.

The various parts of a distribution system requiring protection are the

System of primary feeders; these are equipped with oil-switches.
System of mains; these are equipped with oil-switches.
Distribution transformers; these are equipped with either

a primary circuit-breaker and/or fuses, and/or fuses and/or reverse-energy circuit-breakers on the secondary side; and the Secondary network, generally equipped with fuses only.

The faults to be expected on a distribution system are those from earths and short-circuits on the primary feeders, internal failures inside the transformers, and earths and short-circuits on the secondary mains and branches. On an ordinary radial feeder, protection of faults on the primary are seen to and cared for at the sub-station and/or at the distributing centre.

The possibility of falling conductors and other line accidents are due to many varied causes, varying in different countries and for different conditions. Some of them are:

Decay or corrosion of line-supports;
Unaccounted-for mechanical loads, due to excessive tension caused by falling trees, etc;
Lightning;
Wind storms, particularly in conjunction with sleet;
Arcs from short-circuits;
Breaking of wires of the strand at the insulator;
Broken tie-wires;
Weak joints, kinks, and abrasions;
Weak insulators;
Weak pins and crossarms;
Poor foundations;
Errors in design;
Mischief;
Weak parts due to initial faults and careless handling and erection, and inferior quality of materials.

Service interruptions may result from poor line location, inferior design and construction, and from an inefficient operating and maintenance organisation. No matter how good the design and construction, or how few might be the hazards resulting from favourable line location, if there is a poor operating and maintenance organisation interruptions to service are bound to be increased owing to haphazard or partly finished repairs, etc. as well as increased time in restoring service at every interruption; also the inspection of lines and locating of faults will not be so regular or efficient, and equally sound judgment in the direction and handling of troubles on the lines and in the stations cannot be expected; neither will repairs be as sound and efficient. To give reasonably good service, apart from the fact that a line may be badly located, designed, and/or constructed, it is necessary in cases of interruption of service to give prompt attention, apply sound judgment, know one's work thoroughly, and so forth, if it is desired to reduce the number and the time of interruptions to a minimum.

On the primary lines, flash-overs are about the most troublesome occurrences. These may be due to birds, to dirty insulators, to excessive moisture, dew or soot, to lightning or voltage surges, to the method of construction, and to mysterious causes. Dew formation in the early morning hours has been the cause of much trouble on extra high voltage lines.

Line supports, crossarms, insulators, stays, etc. should be systematically inspected and maintained by treatment, good repair, or replacement; a good operating and maintenance organisation will ensure this. Experience has shown clearly that in direct relation to the efficiency of the operating and maintenance organisation, a relatively more reliable line and distribution system will be obtained. In fact, owing chiefly to an efficient staff, what can be classed as poor practice can be sometimes transformed into a condition almost equal to accepted good practice or good service.

Line poles should be numbered in order that a definite reference and record may be given by the men who are to maintain and make repairs. Stays should all be kept pulled up tight (but not *too* tight), for the staying of a line is its real strength. It is usually during the winter months that particular vigilance must be exercised by the linemen.

A system of emergency switching points on large distributors is of much value and is always necessary. Certain selected points on principal mains and/or on feeders can be equipped with suitable disconnecting switches, by which the lines can be sectionalised and cut off in an emergency. This facilitates better and quicker work, safety for the linemen, and helps to reduce the time of an interruption. Emergency switching points are also necessary for making repairs and for testing purposes, or for making taps, as linemen should not be made to work on live high-voltage feeders or mains.

When lines are located on private wayleave the hazards to the public from broken conductors and current leakage are reduced to an almost negligible value as compared with lines upon public highways and other populous parts, open to pedestrians and/or vehicles. Only trespassers are likely to be injured in case such lines come down, and consequently it is much safer to locate lines through fields than along roads. And, looking at the subject in another way, it would be unreasonable to enforce the same construction requirements for such lines and locations as for lines located on public highways; which comparison may be extended to that of remote territory and scantily populated areas. Obviously, a fallen conductor in a locality having a population of 5000 persons per square mile is a greater menace than where the population is only 50 per square mile. The degree of hazard is also determined by the voltage of the circuit as well as the system used. Technically and practically, the hazard can be determined to a large extent by the way the conductors are arranged on the pole, the kind or type of construction, the number of conductors, and/or circuits on the same line support of the same (or of different) voltages, and so forth. The chances of accidents, when *no* important public crossing or conductors are crossed, are very slight even when the voltage is high (33,000), as few persons will, as a general rule, be concerned with such conductors even when they fall to the ground. The danger is rather when high-voltage conductors are crossed, or running parallel, with low-voltage circuits, and the latter may then accidentally make contact and carry the high-voltage into houses, and in this way subject many to life and fire hazards.

As connections must always be made at the terminals of transformers, switches, etc. *which are always of copper*, it is important in distribution work to use copper and/or copper-alloy conductors in preference to other conductors. Corrosion and dangerous loss of strength due to atmospheric influences, etc. where aluminium and steel are used and jointed to copper, is a very serious matter.

The employment of non-corroding metal for conductors adds materially to the avoidance of hazards from fallen conductors. Copper is the best conductor as judged from every standpoint, and should always take preference over all others, not including very long spans where a higher strength conductor is used (see p. 67). The all-aluminium conductor in small sizes is so light and its yield-point so low that span-lengths in ordinary use require sags so great as to cause almost constant danger of conductors swinging together; and, even with reinforcement, they are lighter than equal sizes of copper and for the same sags would blow about more, thereby often causing crystallisation of the conductor at the insulator support. For reasonable safety, the all-aluminium conductor should not be used in sizes less than a 0·075 sq. in. For distribution work, the advantages of using the smallest sizes of conductors, for any given case, are not so great as appears from the initial saving in place of using conductors of larger size. In districts where the load factor is low or the connected load small, a larger size of conductor may, for the time being, not be warranted by the greater assurance of continuity of service; on the other hand, if the line is to become more important, then it is necessary to put in the larger conductor not only for greater assurance of continuity of service, but also for better voltage regulation, its ability to carry load increases, possible reduced maintenance charges, and so forth. The districts that really call for the smallest allowable conductor sizes are certain very sparsely settled and scattered districts (see p. 248).

In the question of working on lines, one of the most uncertain tasks is the cutting of insulation on normally live conductors when presumably "dead"; the cut in the insulation should be made with every precaution just as if it were alive, until the line can be earthed.

No construction work should be started on any line, feeder or main without the knowledge and permission of a responsible person, for which application should be made.

When work must be done in the vicinity of normally live conductors, two or more men should be present.

No man engaged on construction work, and not attached to the operating staff, should at any time attempt to operate any circuit. A properly qualified person working with such men should be detailed to do such work.

It is also important to see that no construction work is done on or near or around live lines unless there is sufficient clearance to enable the men to work freely without taking extraordinary precautions.

After completion of work, the person detailed should be held responsible for removal of all safeguards and protective devices, if any, and for the restoration of the line, transformers, etc. to normal conditions.

In time of trouble reduction of the time and reduction in the number of interruptions to a minimum is one of the most important matters, and only by analysing the cause of trouble can interruptions be so reduced. Generally speaking, there are two troubles of this nature, namely, partial and total interruptions; the former are usually much more simple to deal with. In handling these, it is first necessary to see if the switch has opened automatically and to examine for oil splash due to violent opening. If this is the case the voltage can, as desired, be brought up to normal, observing the ammeters during this process. If in order, then energise the bus at normal voltage, and try each feeder in succession to locate the faulty one.

At the sub-station or the transforming centre serious damage to transformers may result if a defective feeder is left connected to the bus. It is essential to clear the bus in the quickest possible time and restore the service as well. That is, to clear the high-pressure bus or buses in the station or the transforming centre, as the case may be. Pilot-lamps or voltmeter (if installed) indicate when current is on the station. Energise the lines supplying the distributing centres or those feeders which were in circuit before the interruption occurred. Open all or sufficient circuits or/and feeders so that the load will not be excessive when service is restored and/or when the faulty feeder is put on.

Where the transforming centres are affected, open a sufficient number of feeder circuits or mains so that the line on which service is restored will not be overloaded. When in order, load the station.

In this operation it is important not to connect the circuit at once if large motor installations are on the circuit and do not possess low- or no-voltage releases; such circuits should be kept open for a time in accordance with arrangements agreed upon. On closing the circuit, observe the ammeters and the earth detectors; a relatively slow movement of the ammeter needle across the scale indicates a load or an overload but not a short-circuit—an earth- or a short-circuit is indicated by a violent movement of the needle across the scale.

To restore service, close the oil switch and observe the ammeter and the earth detectors. If the circuit-breaker trips again, determine which phase is defective as shown by the ammeters or the earth detectors on each phase. If the circuit trips a second time and the ammeters do not indicate the defective phase, it may be necessary to open one conductor-phase disconnecting switch and again close the circuit switch. If it does not trip, close the switch just opened and open another phase disconnecting switch, and close the circuit switch again. This operation is performed to find out which phase or phases will hold and which will not.

At all times, all lines of h.p. or l.p. feeders, mains, transformers, etc. should be considered energised unless properly tested for voltage or/and the switches are opened and blocked. Before work is started on any high-voltage circuit it should be tested for voltage; many methods are available for testing whether a primary feeder is alive, the one in common use is that of the switch-rod or hook. For lines operating at voltages up to 33,000 volts, the disconnecting switch-rod method is used. It consists in touching the line conductor with the metal end of the insulated rod and withdrawing the rod slowly to see if a spark follows the movement. The presence of a spark (at such high voltages) indicates that the conductor is alive; sometimes a tube is fitted to the end of the rod touching the line conductor, which glows if the line is alive. For medium voltages, standard gloves, insulating shields, and insulating stools are used.

On certain circuits it is necessary to guard against feed-back through potential transformers. The author once had to replace a man killed by omission of this precaution. In making low-voltage tests it is necessary to remove the potential transformer fuses, otherwise the potential transformer primary winding would form a connection between phases which, when testing, would produce false test results; and, depending on the methods, there is sometimes a feed-back from low- to high-tension where potential transformers are connected.

FIG. 33.—Showing a 6000 volt wood "H" frame construction. (*Henley.*) Note the continuous earthed guard wire, etc.

Also in making low-voltage tests care should be taken not to touch any bare conductor until after the test for "foreign" voltage has been made. This is because low-voltage tests often require handling in close approach to high-tension conductors, and apart from danger to life there is a likelihood of burning out the testing set. Hence, the first requirement for personal safety and protection of the testing set is to test for foreign voltage. The switch-rod test may be applied here. A charging current may or may not be maintained while the rod is being withdrawn, and there may be an entire absence of a spark; sometimes the absence of a spark is not a sufficient test that no foreign voltage is present. In such cases it may not be obvious that the voltage is too low to produce a noticeable spark, yet the actual voltage may be a dangerous one.

For the primary feeder or any high-voltage line, it is necessary first to test for foreign voltage just as in the case of low-voltage lines. If foreign voltage is indicated it must be sought out and removed. If no foreign voltage is indicated, connect leads of the high-tension testing set to the line conductors and earth one phase. With the feeder regulator (if any) adjusted to give minimum voltage, close the oil switch in circuit with the testing set. Slowly raise the voltage to a specified value unless an excessive current shows up at a lower voltage; observe the earth detectors. If there is no current flow, raise the voltage to normal and maintain for about one minute. Reduce the voltage to a minimum and open the oil switch of the testing set. Then disconnect the earth from the phase conductor just tested. Test each phase conductor in like manner. Transformer and insulation tests and earth tests may be carried out in the same way. Line-phase and transformer-phase tests should have their correct phase relations indicated by a zero reading on the synchroscope and/or by the lamps remaining dark.

Oil-insulated self-cooled transformers are the type generally used on distribution lines. These transformers should have the oil tested periodically for moisture. From time to time it is necessary to see if the oil stands at the proper height in the gauge. At the same time inspect the leads for oil siphoning, and see that the insulator bushings are free from coated dirt, and that there are no loose connections. It is advisable to take samples of oil about every six months for the purpose of testing the oil. These samples should be taken from the bottom of the transformer case. If the transformer case is supplied with a clean-out valve at the base, this valve may be opened and a sufficient quantity of oil drawn off for a proper sample. If there is no valve or plug at the base, then, for the purpose of drawing off oil from the bottom, take a long tube of glass or fibre (preferably the former), close the top end of tube with the finger tip, and lower the other end through the oil until it reaches the bottom of the case; raise the tube about one inch off the bottom, then remove the finger. This allows the oil from the bottom of the case to flow up into the tube. Replace the finger over the top end and remove the tube from the transformer. The oil entrapped in the tube is a fair sample of oil from the bottom of the case.

A method for locating faulty insulators is shown in fig. 34. It consists of a long wooden pole with wire centre, a steel spike at the top, also an antenna consisting of fan-shaped wires at the top, as shown. About 5 ft. from the ground are two binding posts which allow the connection of amplifying receivers (ordinary telephone head-set will do) for detecting current leakage.

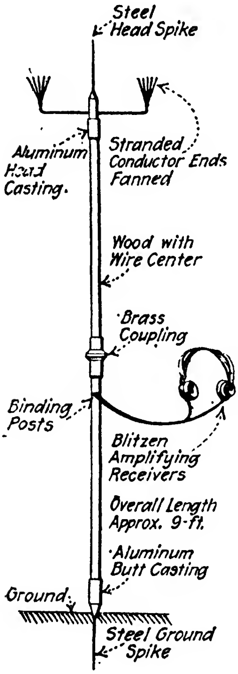


Fig. 34.—Showing telephone-receiver method for locating faulty line insulators.

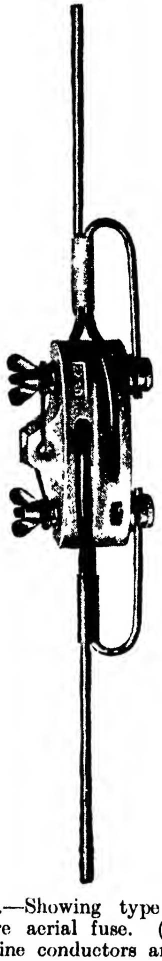


Fig. 35.—Showing type of 60-ampere aerial fuse. (*Henley.*) The line conductors are interlocked, so that, should the porcelain be accidentally broken, they will not fall to the ground.

During and after storms, secondary lines exposed at some part to primary lines are liable to have become crossed through actual contact or, more often, through tree leakage with the higher-voltage lines. When men work upon low-voltage lines at such times they should apply special precaution to make sure that there is no such dangerous leakage current by effectively earthing the supposed "dead" circuit to be worked upon.

On the question of safe sizes of fuses, the following figures give the approximate safe fusing and normal carrying capacities for copper wire, also for lead fuses of lead-tin alloy consisting of 25 per cent. tin and 75 per cent. lead.

TABLE XLI.

SIZES OF COPPER FUSES.

Diameter of Wire. (Inch.)	Equivalent S.W.G. Size.	Fusing Current (Fusing Time =1·0 Minute). (Amperes.)	Maximum Safe Working Current. (Amperes.)
0·0092	34	8·6	4·3
0·010	33	9·8	4·9
0·0108	32	11·0	5·5
0·0120	..	12·8	6·4
0·0124	30	13·5	6·8
0·0148	28	17	8·6
0·018	26	22	11
0·022	24	30	15
0·028	22	41	21
0·029	..	43	22
0·036	20	62	31
0·040	19	73	37
0·044	..	86	43
0·048	18	98	49
0·052	..	111	56
0·056	17	125	63
0·064	16	156	78
0·072	15	191	96
0·080	14	229	115

SIZES OF LEAD-TIN ALLOY FUSES.

Diameter of Wire. (Inch.)	Equivalent S.W.G. Size.	Fusing Current (Fusing Time =2·0 Minutes). (Amperes.)	Maximum Safe Working Current. (Amperes.)
0·020	25	3	2·0
0·022	24	3·5	2·3
0·024	23	4	2·6
0·028	22	5	3·3
0·032	21	6	4·1
0·036	20	7	4·8
0·048	18	10	7·0
0·064	16	16	11·0

The functioning of a lightning protector, the installation of a continuous earthed-wire guard from pole to pole, and the installation of an overhead earth-wire, all provide an easier path for the lightning to reach the earth; the first and third are in certain cases accepted as good practice, but the second in its present form is often a danger, yet can be made into a necessary expense. For the line itself there is provided a continuous line conductor strung from pole to pole which is mounted on the best insulators, then—according to requirements enforced in this country—the supports are deliberately earthed, thus providing, not unlike the lightning conductor, an easier path for the lightning or the opportunity for a surge voltage to puncture the insulators; this danger is further increased because the line itself forms the highest (wires or conductors) above ground, and therefore is the one likely to get the greatest charge from the lightning.

Several of the different methods which may be used for giving protection to overhead lines involve:

Use of better line insulators;
Earthing the neutral point of transformers;
Retaining the insulation of wooden poles and/or crossarms;
Avoiding the use of metal up the pole as much as possible;
Installation of protection tripping devices;
Installation of overhead earth-wire, insulated from the wood pole, for *safest* line study fig. 32B, and pp. 23, 196–201;
Installation of lightning arresters and/or choke coils.

Although power service interruptions can be reduced to an operating minimum by proper location, care in design, construction, operation, and maintenance, it is sometimes necessary to put up several circuits and to locate switches correctly, etc. to facilitate better maintenance and permit of a more suitable system of distribution for the particular territory.

With respect to designs, these are based on the most severe climatic conditions (not necessarily prevailing in the district—a condition that should be provided for), and the line-supports, insulators, conductors, etc. are either chosen or specially put up for such conditions; yet, in spite of providing the best design and putting up the best construction, failures *do* occur, and will always occur from one cause or another, such as a weakening of the insulation with time, from polluted atmosphere, from unavoidable electrical strains due to mistakes, inferior construction standards, and unavoidable mechanical stresses put upon the system. For best system and line, study fig. 32B, and pp. 15–25, 196–201.

Some of the troubles more likely to be expected and the conditions of service to be met with in actual practice are:

For the isolated neutral system, if an earth occurs on any phase conductor, the normal-frequency stresses are increased 73 per cent. The resulting arc from the short-circuit may produce enormous stresses between turns in the power transformers, and the abnormal voltages which are likely to occur may cause break-downs on other phases and/or cause a short-circuit between phases due to line-insulator failures or to break-downs in the power transformers themselves.

System neutrals are sometimes earthed direct, sometimes through resistance, and at other times through a reactance. Resistance is introduced in order to limit the short-circuit current. Reactance is introduced, and is adjusted to balance or reduce the capacity current in the arc to zero, the idea being to suppress the arc; these are not used in the neutrals of overhead distribution systems.

As far as is possible line location should result in a minimum length to reach a given load and/or supply. At the same time it should permit of a minimum number of poles as well as angles if they can be avoided. A location should offer favourable cost for easements, at the same time permitting low cost for support setting, accessibility for transport, distribution, erection, inspection, and repairs. Anything between these conditions and the extreme opposite can be obtained.

Some supports may be unfavourably located, subjecting the line to many angles requiring special construction or use of too many stays, subjecting it to prevailing winds or to maximum winds, to adverse climatic conditions, and be so located as to be in the path of lightning, sand or dust storms. The construction may (or may not) be of the best design as regards the type and strength.

There may exist an excessive depreciation of line-support, crossarms, and/or stays due to excessive loading, etc. due to climatic and other conditions.

The unbalanced stresses may not be properly provided for.

The preservative treatment or the galvanising may be poor (too thin) and the soil not suited to the materials used.

Failures may occur owing to the weakness of the foundations or settings, causing an uplifting or an overturning of the poles.

The present-day construction and use of the continuous overhead earthed guard is practically ineffective, and is the cause of many of the weaknesses already referred to above.

The line insulators used may be poor and the mechanical design inferior. The electrical strength may be too low for the district, and the insulation strength may be reduced as much as the insulating value of the insulators themselves by using a continuous earthed guard, and it may be weakened too rapidly by the same and other abnormal stresses.

There may be an excessive uplifting or/and at other points an excessive downward pull of the line-conductors.

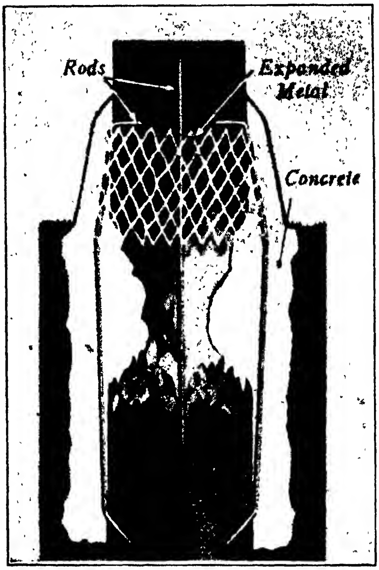


Fig. 36.—Method of strengthening wood pole at ground-line. Cut away all the rot to firm wood, fix reinforcing rods as shown, then fill with concrete to cover the rods below and the expanded metal above the ground-line. (The illustration shows an exaggerated case of rot.)

Some of the insulators may have too tightly fitting metal or badly fitting pin.

Depreciation and failures due to over-testing and to unaccounted-for causes.

The use of too many insulators, or to insulators being over-mechanically stressed. The insulation of a line is designed for one condition, namely, that of adequate insulation for normal operating conditions and for a specified normal voltage. In practice we have quite different conditions which cannot very well be calculated. What is required to be known, perhaps more than anything else, is the maximum to which it is possible to determine abnormal strains such as over-voltage, not for a normal line, nor for any particular condition, but for abnormal strains occurring at (or after) the time insulation has been weakened from some cause or other.

Line trouble may be due to a poor choice of material for line conductor necessitating unsatisfactory span-length and/or greater power loss.

The inaccurate or careless stringing and/or handling of the conductors. They are sometimes due to flash-overs from the conductors to earth or phase to phase, due to small separation of the conductors, or birds, and steel construction, etc.

It may come from swinging of the conductors. The swing is greater the lighter the conductor for a given span, the greater the sag and the freer the swing of the support (the insulators); this swing must be allowed for.

Neglecting such matters as mistakes in design, in erection, and in the operation, some of the principal causes of trouble and of power-service interruptions are difficult to understand. Many disturbances which cause failure and interruptions can be guarded against by maintaining an efficient organisation.

The advantages of earthing the neutral of any system are well known. An earth on any line conductor of an earthed-neutral system produces a short-circuit which causes a reduction of voltage on the short-circuited phase and an uncertain over-voltage on the unearthed phase. Thus, as soon as one phase becomes earthed there is a short-circuit on that phase of the earthed-neutral transformer winding, and a reduction in voltage on all three phases due to armature reaction in the generators; hence there is no over-voltage stress on any part of the system.

Taking the two systems, *i.e.* the isolated-neutral and the earthed-neutral systems, there may occur as many cases of line failure, such as break-down of insulation and other troubles common to a line; but as soon as one phase of the latter system becomes earthed, there is a short-circuit on one phase of the circuit or system resulting in a reduction of voltage on all three phases. In consequence, secondary break-downs are almost unknown on an earthed-neutral system, and the troubles are confined to one point. On the other hand, the isolated neutral system often follows with insulation break-downs on the unearthed phase conductors, then followed by break-downs at other points of the system which happen to be weak and/or partially earthed; the earthed-neutral system is practically free from secondary break-downs, and the current in the short-circuit flows over definite and known paths, which makes it possible automatically to introduce selective action by means of relays, etc., thus offering better service to the entire system than the isolated-neutral system. Moreover, where two or more lines are concerned, it has much greater advantages over the isolated-neutral system.

The principal argument in favour of the isolated neutral is the possibility of continuing operation in case one line conductor becomes earthed owing to a broken insulator or broken conductor, or from any other cause. In accordance with the regulations of this country, this argument does not stand. Holding on to an earth in order to avoid interruption of service frequently results in break-down of the insulation in other parts of the system operating with an *isolated* neutral. Furthermore, the earthed neutral system (see fig. 32A) has the advantage for operating with a broken conductor and/or a burnt-out transformer phase-unit.

Earthing the neutral at one point only is the requirement for this country, the earth being made at the generating station or supply end only. In practice, one, two, or more neutral earths are found necessary. The multiple earth has, among other advantages, the effect of reducing the impedance (or length of the impedance path) for the short-circuit current, and ensures that the earthed phase conductor is brought to approximately zero potential from the point of the accidental earth to the earthed-neutral of the transformer. It is also done to ensure that, even though part of

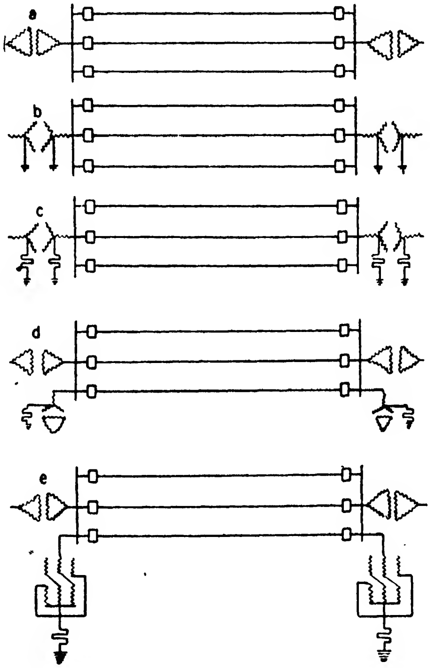


FIG. 37.—Primary side of distribution from the main sub-stations to transforming centres, showing various methods of earthing (and making) the neutral. (Where the star point of transformers is brought out, this point can be earthed, either solidly or through a resistance. When there is no neutral point available, an earthing transformer may be installed. Earthing transformers are usually connected either *star-delta*, with the star point earthed, or zigzag, with star point earthed; both methods have their particular advantages. When the *star-delta* earthing transformer is used, the star point may be earthed either solidly or through resistance. If desired, a load may be taken from the *delta*-connected secondary of the transformers. The advantage of the zigzag-connected earthing transformers is the relative cheapness of it, since with it no secondary winding is required, and thus it is somewhat cheaper than the *star-delta* transformer or bank of transformers for earthing.)

the system is cut off by trouble or otherwise, the remainder of the system will still have an earthed neutral (see page 200).

In the operation of any line it is necessary to have in mind its possible or known weakest part, which invariably is the insulator, and that no matter how strong may be the other parts of the line or system, they will stand up only to the weakest part. Therefore it is advisable to design a line or system so that insulation is the best, and has the longest and the most economic life.

In rural construction it often becomes necessary to choose between cost and a safe design and construction. The choice usually centres on lengthening the span so as to reduce the number of poles, insulators, and hardware, but the span increase should include consideration of economic life and service interruption hazards, and these should not be overlooked.

For distribution lines in general it is not likely that there will be much over-lengthening of span, although lengthening the span (having proper regard to economy and hazards) is one of the best means for decreasing the cost and at the same time giving satisfaction. This applies equally well to secondary mains, provided the regulations are relaxed regarding taking taps for services at the pole *only*.

In the design of a wooden-pole line it is necessary to keep the line insulation unchanged, *i.e.* see that each conductor support (pole, crossarm, and pin) provides all maximum possible insulation to permit of the highest possible flash-over voltage.

Where wooden poles or frames are used, the best practice is to have them thoroughly impregnated throughout their entire length to increase their resistance as well as increase the life of the pole. Such a pole stands much less chance of being struck by lightning, as it is not converted into a lightning conductor or/and a lightning arrester, because of the absence of metal and earths so commonly attached *direct* to the pole. Where it is the practice to employ the continuous earthed wire or cable, if it is not insulated from the poles in some way it will (as previously referred to) tend to reduce very greatly the insulation value of the wood and/or line, endangering good operation by increasing bird and other troubles.

Maximum permissible earth resistance in New Zealand is 10 ohms, and for a line (1) having an earth lead; or (2) an earthed-neutral conductor of a three-phase system; or (3) an intermediate wire of a 3-wire system which is normally earthed, we have a condition of a line classed as *dangerous* if at any point along its length the resistance to earth is *more than* 25 *ohms* (see also p. 237).

The secondary earthing conductor should not be of any great distance from the nearest earth connection, and it should be of sufficient size to give the required conductance and current-carrying capacity. It is more than objectionable to have a secondary circuit break its earth connection by blowing of a fuse while the primary transformer winding remains connected to the line. To ensure permanent continuity of the earth connection, earth connections and fuses should be so placed in relation with each other that the secondary transformer winding is always connected to earth. Where a secondary circuit is exposed to a hazard through the transformer winding—not necessarily located below a primary circuit which also offers a hazard—the only fuse which need blow to protect against high-voltages on the secondary is the primary fuse of the transformer.

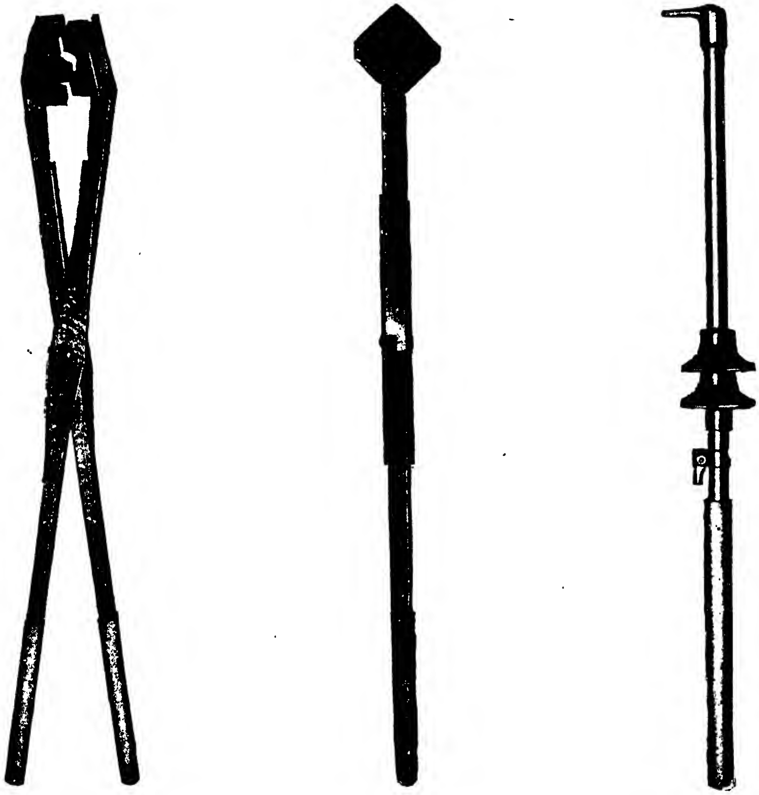


FIG. 38.—Insulated tongs for removing fuses, and isolating-switch and link operating-pole with earthing ring. (*Henley.*)

This and other matters mentioned all point to the necessity for low resistance in the earth connections. Taking, for example, a case below the 25 ohms mentioned above, a single earth connection of 24 ohms resistance would give rise to 240 volts between secondary and earth with scarcely enough current flowing to blow a 10 ampere fuse. An earth resistance of 24 ohms carrying, say, 50 amperes—equal to a small-sized primary distribution circuit—would cause $IR = E = 50 \times 24 = 1200$ volts drop between the earthed conductor and the secondary and earth. We thus have a life hazard from a high-earth resistance, yet this condition is to be found on distribution transformer installations. The power wasted in this case by the current passing through the earth connection is in the order of $P = EI = 1200 \times 50 = 60$ kW. This current flow would more likely increase the earth resistance by drying the earth around, thus raising the voltage still higher, and, depending on the location, such a condition would be both a life and a fire hazard.

The strength of poles when used jointly by telegraph and/or telephone lines and power lines is naturally determined by the hazards involved. Such wires should not be placed above power lines because of the relatively greater danger due to their liability to failure. On account of the inherent life hazard from communication (telegraph and telephone) wires they can be stressed to relatively higher tensions than power conductors. As they are relatively small in diameter they will fail, under extreme weather conditions, before their supports which have a larger factor of safety. This condition decreases the maximum allowable transverse load on the supports, and the pole consequently may be designed with a smaller assumed load than would be suitable were all of the conductors power conductors. It is therefore obvious that by joint use the total cost of line construction can be reduced considerably.

One of the most serious troubles and costs of rural distribution for this country will be that of providing guards, intended for the protection of circuits other than power conductors, such as telephone and telegraph lines, as well as for highway and other crossings. Unfortunately, this kind of construction, and the possible safety originally intended, was started with an awkward idea, *i.e.* that of making a proper mechanical job of the guards, in place of devoting the same amount of money in making the line itself sound mechanically and in such a way as not to fall.

At crossings, small, or solid, conductors should not be used. since slight abrasions and surface injuries affect their strength to a comparatively greater degree. Stranded conductor is better than solid, but copperweld-steel cable is far superior, as also is copper alloy (see p. 67). For an important crossing, all that is necessary is to use copperweld-steel, copper-alloy, silicon-bronze, or duplicated stranded all-copper cable. Tie-wires are not quite satisfactory for such places. Double insulators and double galvanised steel insulator-pins (extending well up into the insulator) or extra strong strain insulators should be used. For the double (split) stranded

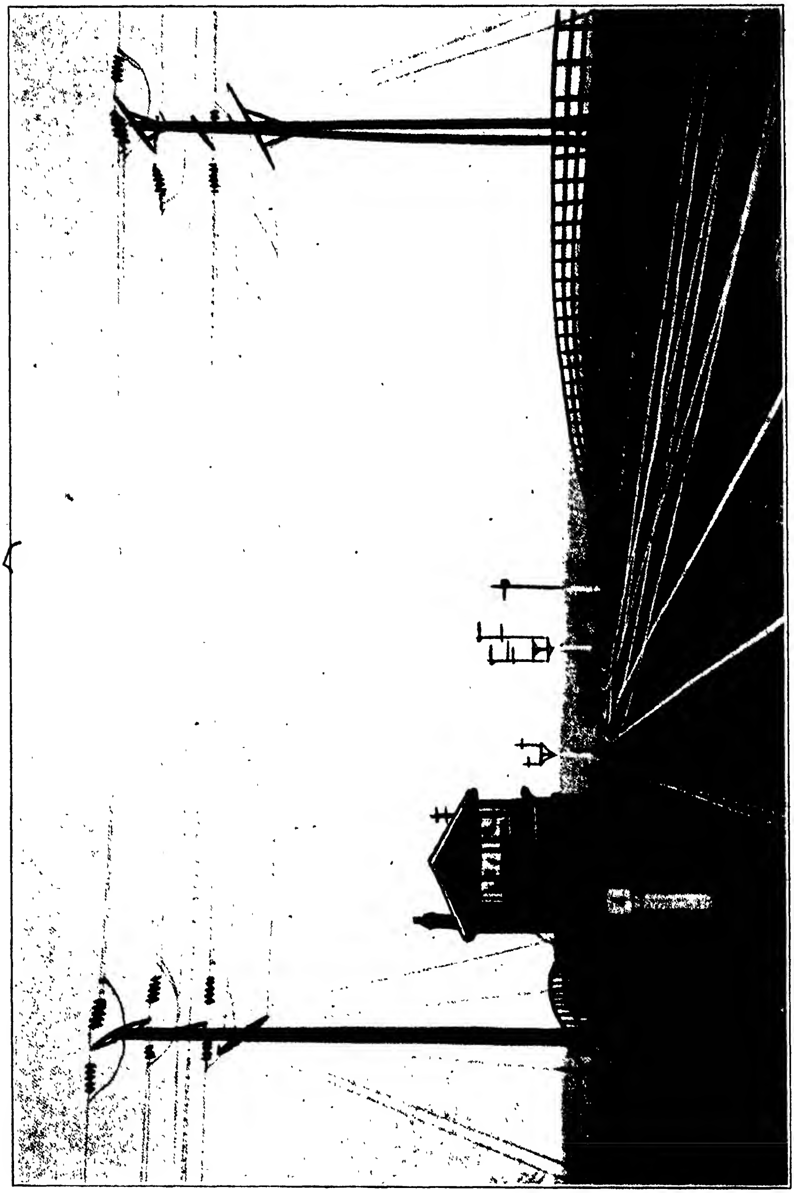


FIG. 39.—Excellent example of 66,000-volt crossing, showing duplicate strain insulators and simple lace guard. (*This is in the north of England.*)

copper conductors, four pin-type insulators should be used preferably at each line-support. *Single-wire bridle crossings are best.*

A guard to be satisfactory should almost enclose the line conductors, as the broken wire or conductor rarely, if ever, falls vertically and within the confines of a flat net of very restricted width; when conductors fall under tension, the ends usually whip out laterally or curl in a spiral from the effects of hardness and the original reeling, etc.

The object of a guard is to afford protection against a possibility of accidental contact (excluding the guard) in case of conductor failure, or to ensure that a falling conductor shall become earthed before it can cause any damage, and also to prevent a broken conductor from coming within reach of ground. In practically every case the most reasonable place for a conductor to fail is at the insulator, where it might fuse or soften should the insulator crack or break. Just why an earth should deliberately be made to cause an interruption of service, and perhaps other damage, while means can be provided to keep the conductor insulated and quite out of reach or danger, is not obvious. Such so-called guards have been, and very often are, a source of much more danger to people and to service than that which they were made to guard against.

Other than the line itself, where additional protection is necessary, one of the neatest span-crossing arrangements is that of split-conductors, using double insulators (one for each conductor) with clips at intervals across the span, so that if any one of the conductors should break, it is kept well out of reach of vehicles and people passing along the road beneath. Line-supports at crossings, if properly stayed or made stronger than the others in the straight line, will hardly fail at the crossing, and if the attachments to duplicate insulators are such that in the event of a clamp or insulator failing (the conductor still being held) there would seem to be no reason for causing a disturbance—often affecting all the circuits where the continuous earthing-guard method is used—as would be done by the installation of an earthed cradle, while a live conductor can remain free and safe and well out of reach and be spotted on the first inspection trip, as well as permit uninterrupted service over all the circuits, including the one with the broken conductor. Split-conductor is neat but *poor practice.*

Where wood *poles* are used, the crossing span should be side-stayed in both directions and should (where possible) be head-stayed away from the crossing span, and the next adjacent poles

—on each side of the crossing span—should be stayed toward the crossing span. In the design of a crossing span, the stress and clearances should be calculated for a wider range of temperatures and for a greater wind pressure than is given the ordinary spans. For urban lines in general this is hardly necessary because the spans are for the most part relatively short.

FIG. 40.—Good example of ordinary road-crossing and angle in the line. Two circuits each 3—0·1 sq. in. bare copper strands and a continuous earthed guard wire located below. 35,000 volts. With proper size, use, and construction of *one* continuous earthed guard wire, a double three-phase 3-wire line as shown here could be converted into two three-phase 4-wire circuits delivering many times more power, be safer, more reliable, cost practically the same, and have an earning capacity very much greater.

So far no exception to existing regulations of this country is given to rural construction. It is specified that where the pressure to earth exceeds 325 volts (alternating current), precautions shall be taken to prevent danger, and provisions made to render any line conductor dead in the event of it falling, owing to breakage or otherwise. Also that all metal-work other than conductors shall be permanently and efficiently connected with earth. For this purpose a continuous earth-wire shall be provided and connected with earth at four points in every mile, the spacing between the points being as nearly equidistant as possible; or, alternatively, the metal-work shall be connected to an effective earthing device at each individual support. The design and construction of the system of earth connections are sometimes made such that when contact is made between a line conductor and metal connected with earth, the resulting leakage current would not be less than twice that required to operate the devices which make the line dead.

Provisions laid down for this country, with the idea of preventing danger from leakage, are given as follows:

> When the pressure to earth exceeds 125 volts a.c., precaution shall be taken to prevent danger from leakage by the provision, in case of wooden poles, of:
>
> Connecting a bonding wire to the supporting metal-work of all insulators, the bonding wire terminating at the lowest part of the supporting metal-work, and being at a height of not less than 10 ft. from the ground, *and*
>
> Other means approved by the Electricity Commissioners.

Where lightning conductors are used, or other uninsulated conductors are run down wooden poles to within 10 ft. from the ground, the precautions for the prevention of danger from leakage shall be as for metal poles, which specify :

> An earthed wire, running from pole to pole and connected to the poles.
>
> A suitable metal framework to support the insulators carrying the line conductors, the framework being insulated from the pole, but connected to the neutral conductor, *or*
>
> Other means approved by the Electricity Commissioners; *and*
>
> All stay-wires, other than those which are connected with earth by means of a continuous earth-wire shall be insulated to prevent danger from leakage. For this purpose an insulator shall be placed in each stay-wire at a height of not less than 10 ft. from the ground.

With the exception of the latter, the author considers that this practice should be modified. As regards the latter, a stay cable is always set at an angle with the ground-line, and for wooden poles and where properly installed the stay invariably takes the whole of the stress, and as it is generally of corroding metal, it is the most likely part of the line to fail from mechanical reasons, and, from this view-point, the continuous earthed wire and the conductor should have the same minimum height. Its failure is often at the insulator; in any case, when it does fall it will drop into a vertical position and will then be at a height much less than 10 ft. from the ground.

For current leakage limitation, regulations for this country require that the insulation of "medium-pressure" mains shall be so maintained that the leakage current shall not under any conditions exceed *one-thousandth* part of the maximum supply current, *i.e.* 1/1000, where I = maximum supply current. This is unlikely for distribution in view of the methods adopted and requirements for earthing at one point only, etc. Multiple earthing should also generally reduce the risk of interference with communication circuits (telegraph and telephone) under fault conditions. The limitation of current leakage is best found and properly dealt with by the installation of proper protective devices and an efficient maintenance staff. The best earth connections are those in multiple and not too far apart (see also p. 198), and the best are from water piping systems, which give an approximate minimum of 0·10 ohms resistance. To illustrate, let us take an ordinary three-phase feeder of 3000-volts, designed for a maximum carrying capacity of 200 kW; where the current at full load is 38 amperes, limiting leakage current to 1/1000, we get

$$R = 1/3000 = 38/3000 = 0{\cdot}01267 \text{ ohms},$$

a condition very wide from actual practice.

The secondary circuit voltage taken from distributing transformers, and which enter residences, can well be classed as a dangerously high voltage (*i.e.* $\sqrt{2} \times 240 = 340$ volts); moreover, it is very closely interlaced with dangerous high-voltage windings, which provides the most important reason for *earthing* the neutral. When dependence is placed on an earth for the purpose of keeping the earth potential fixed, it should be made carefully, because if badly made it will be inadequate for the purpose, and both life and fire hazards may be unavoidable. The voltage rise of the earthed part above earth potential is equal to the earth current times the impedance (IZ) in ohms of the earth connection, and for safety this should be kept below a value which is dangerous to life,[1] *i.e.* not higher than about 250/2 = 125 volts a.c., *above earth*; hence,

---

[1] **340 volts will kill, and 66,000 volts can do no more; a lower voltage than 125 volts a.c., or $125 \times \sqrt{2} = 177$ volts d.c., above earth, has been known to prove fatal (note p. 202).**

on this basis the lowest *effective* resistance to earth may be taken as 125/I, where I is the maximum current flow through the earth connection. This so-called "safe" value for voltage rise of *the earthed part*, such as the earthed neutral, opens up an interesting subject for discussion.

Power conductors of dangerous voltage are usually well out of the way and people avoid them, and if linemen have to work on them they take care to be well insulated from earth. It is safe practice to have the distribution neutral and transformer secondary conductor neutrals connected to the same neutral conductor (or bus) and earthed at, or not far from, the transformers, giving the net result of a number of earths in multiple. It is found that the total resistance of these neutral conductors to earth is generally low, and because of this it also forms a valuable earth for the sub-station or station earthing, and can be connected to the station earthing system where possible. It thus gives a direct metallic return to the transformer neutral, and to a large extent relieves the station earthing from carrying unbalance or fault current.

For distribution arresters, distribution transformers, and distribution circuits, the resistance to earth normally should not exceed 10 ohms. A water piping system makes the best earth, it being as low as 0·10 ohms or ranging between this value and about 8·0 ohms. For distribution and service neutrals, earth plates and pipes connected in multiple are best where a water piping system cannot be reached. Earth plates buried in swamp, clay, loam, or sand, usually limit the resistance to a maximum of about 25 ohms and a minimum of about 3·0 ohms; the resistance varies with the season. Driven pipes, in multiple, to a depth of about 6·0 ft. in clay or loam, offer a lower resistance than earth plates. Single pipes (making isolated single earths) are generally used on distribution transformers, services, and arresters; they are best when driven about 6·0 ft. into clay or (failing this) into loam, or (failing this) into gravel; as already mentioned, the resistance of earth varies with the season, *i.e.* wet, dry, frozen, etc.

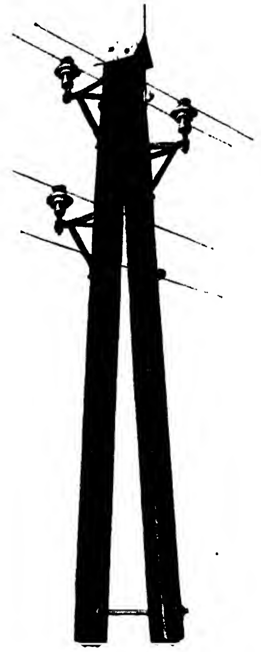


FIG. 41.—Wood construction for 3-wire circuit. (*Henley.*) Note the iron brackets and the continuous earthed guard wire, etc.

The E/I meter method of checking the earth resistance connections is the most reliable; the measured resistance to earth is equal to the voltmeter reading *divided* by the ammeter reading.

With reference to relay protection, what should be aimed at is a relay that operates for all types of faults whether to earth or between phases; that disconnects the feeder or both ends under all conditions; that is practically instantaneous in action; and one whose action is independent of the direction of the flow of power under normal or fault conditions.

A fundamental system of protection against faults *producing abnormal currents* is the system depending on over-current relays with differing time adjustments, such time adjustment, in general, becoming longer the closer the generating station. There are also many relay systems of the pilot-wire transmission type, and a general system of protection against abnormal current-producing faults, based on the principle of balancing out of relay circuits all current except the fault current, thereby causing the protective relays to function in response to the fault current alone. There are two methods of applying this principle, one by means of a series differential connection in which the two ends of a circuit are balanced against each other, and the other by a parallel differential system which may be used where a circuit consists of parallel paths which may be balanced against each other. There is, in addition, another system of protection using current alone, and there are a number of systems which depend upon the use of both current and voltage. Some of these, such as differential *earth* relaying systems, use both the fault current and the fault voltage; others, such as directional current and directional power systems, utilise the circuit voltage and total current, and certain other devices, such as the impedance relay, utilise the total current and fault voltage. The present tendency is toward the maintenance of system integrity by relays such that they will:

> Detect and give warning of approaching faults or conditions which may cause faults.
>
> Respond to abnormal conditions resulting from the occurrence of faults to isolate the particular circuit at fault.
>
> Permit of adjustment with such time delay as to function only upon the fault of the first and second lines of defence, which is a form of "follow-up" system (or "second-line defence") in the form of a second system of relays to function in case of failure of the first system, applied either to the same circuit-breakers as the primary defence, or to other nearer sources of energy.

Balanced protection relays for lines and transformers are much used in this country. The oldest form of protection much used universally is the fuse. At the present time, some of the most important system protections by means of relays, are:

Direct-current polarised relay used for overcurrent, overvoltage, undercurrent, under voltage, reverse power, polarised potential, etc.

Automatic network relay for the control of a.c. network circuit-breakers; this connects transformers to the network when capable of supplying load and disconnects them on reversal of energy flow, and will operate on the magnetising current of transformer.

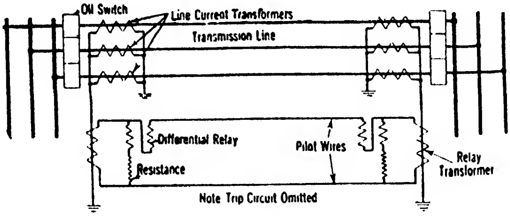
Network relay for protecting low-voltage a.c. transformers against a faulty distributing transformer or feeder.

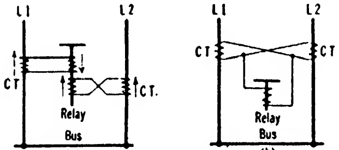
Power directional over-current relay, offering power directional protection against earth faults, and phase-to-phase faults where, for any reason, single-phase directional elements are preferred to a polyphase relay.

Earth relaying is considered absolutely necessary to isolate an earthed line immediately so as to reduce chance of injury to people who may come in contact with or approach an earthed conductor, also to reduce the resultant damage to apparatus and lines by removing an earth as quickly as possible from the system. Where wooden crossarms and poles are used, the earth currents encountered are relatively small, and sensitive earth relays are required to recognise these small currents. Where the system is "dead" earthed, the relaying for earthed faults is comparatively simple where the fault current obtained is as great as the load current. In such cases, however, the current for earth faults is comparatively small, due to contact resistance at the point of the fault. Where this condition exists, the phase relays may not protect the line for earth faults, and other means of protecting the lines for earths must be used. Many different schemes for earth protection have been devised, some of which are:

Impedance earth relay;
Balanced current earth relays for parallel lines;
Power directional relay;
Power relay with instantaneous time, but interlocked with over-current non-directional relay for timing;
Power relay with self-contained timing element;

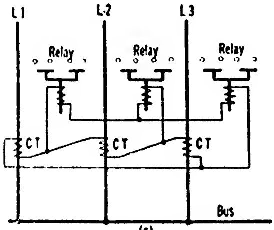
Over-current non-directional relay interlocked with directional elements of phase relays;





(a)
Magnetic Differentiation

(b)
Electrical Differentiation



(c)
Electrical Differentiation for Three Lines

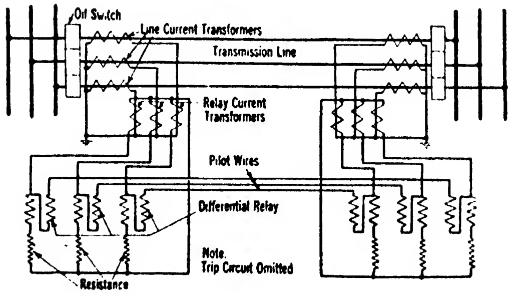


Fig. 42.—Differentiation relay methods, with and without pilot wires, for the protection of one or more lines.

Over-current non-directional relay in neutral of current transformer circuit.

The over-current non-directional earth relay is satisfactory for use on radial feeders or other locations where directional protection is not required, such as transformer differential protection or on radial lines. In connection with such uses, a relay with a low operating range, and one which puts a small volt-ampere burden on the current transformers, is very desirable. This type is very sensitive to small earth fault currents, and, owing to its low volt-ampere burden, does not overburden current transformers which have other apparatus than relays connected to them. The low energy power directional earth relay using inside *delta* potential is quite satisfactory. In this scheme the same potential is used as with the power relay, but it is used only to operate the directional contacts of the relay, the relay having a separate over-current element similar to that of the over-current relay. The over-current and directional contacts are connected in series as in other power directional relays. By using this scheme, the directional elements may be made to operate on a very small number of watts, thereby making it sensitive to very small earth currents.

Relays should operate quickly so that damage is not done to the insulator, conductor, or crossarm (if of wood) in case of flash-overs and earths. Selective relays are necessary for economy in the amount of conductor, better regulation, flexibility, and freedom from service interruptions. The protection problem is not only to protect and clear a faulty circuit or line, but in case of failure to do so, and to clear a good line from the excess current flow and give protection from abnormal conditions.

For primary network protection, the pilot-wire systems are most suitable to concentrated networks and relatively short lengths of feeders and underground cable systems. For parallel feeders differential protection can be employed, but over-current and differential protection schemes are sometimes preferable on account of greater flexibility and less wiring. Radial and loop sections may have over-current protection with successive time settings, either with or without directional selectivity, or, one of the pilot-wire schemes can be employed. For the secondary-network protection *fuses* are in general use, but provision is sometimes made (depending on conditions) for disconnecting transformers by either power directional or over-current protection.

As a general rule, a rural service would, for economy, take the form of a single feeder consisting of one primary supply, and, where the secondary circuits of several distribution transformers are so close that they could with economy be connected together through the secondary main, they would be so connected, thus permitting:

Better continuity of service in case a transformer should fail or burn out;

Better voltage distribution on the secondary network as a whole;

Advantage of diversity between the loads of the secondary network.

The only objection to this simple method of rural distribution is that no provision is made for giving continuous service in case the primary feeder or primary protection should fail. To commence with, it would rarely pay to put in a duplicate feeder supply, but as such a service becomes more and more important it would pay to run another primary feeder and/or a polyphase line depending on the class and size of load. Usually future requirements and service conditions determine the requisite modifications.

For rural electricity supply it is very desirable that all its aspects should be studied carefully, including the non-technical phases, such as that of keeping prospective consumers specially interested in electric service, carrying on and/or completing negotiations for line extensions; in fact, anything of a social nature tending to improve rural or other line development should be studied. At the present time it is generally agreed that electric service should be made available to rural populations (in particular) as rapidly as possible and, to do so economically, overhead lines *must be constructed to conservative standards.* In the planning of such developments, it is necessary first to:

Study the location (or locations) of existing sub-stations or distributing or/and transforming centres;

Decide as to the right location of a transforming or/and distributing centre so that the particular territory or district can be served to very best advantage;

Study the size and shape of the district so that it can be divided into definite service areas, each to be served by its own sub-station or transforming centre or distribution transformer;

Study the best system and method and routes for the main-line service;

Canvass along existing rural and other lines, if any, for the purpose of increasing the consumption per consumer per mile (or per 1000 yds.) of line;

Canvass the most promising areas where rural or other service lines are being (or intending to be) planned;

Plan joint use of existing pole lines in the neighbourhood;

And obtain all possible information for respective loads and line extensions, such as:

Number of consumers per 1000 yds. (or per mile) of route;

Length of line in miles;

Average number of consumers per mile of line;

Average load applied for in kW;

Average initial connected load in kW;

Average kW connected load per consumer, for light, power; heat, farm equipment and plant, miscellaneous, *respectively*:

Average size of transformer, required in line, in kVA;

Average transformer demand factor;

Line power factor;

Demand factor of line;

Percentage line losses;

Percentage transformer losses;

Percentage meter losses;

Month and kW.-hour maximum use of energy;

Month and average kW.-hour maximum use of energy per consumer;

Month and kW.-hour minimum use of energy;

Month and average kW.-hour minimum use of energy per consumer;

Annual kW.-hour delivered to consumer's service;

Annual average kW.-hour use of energy per consumer.

The exact number of kW.-hours supplied is not easy to obtain because of the errors, etc. such as those in the meters. The number of unaccounted-for kW.-hours is the difference between the total kW.-hours registered per month on all meters feeding into the distribution system and the total kW.-hours registered during the same month on all meters over which energy is distributed; in other words: let the former equal P_s and the latter equal P_d, then

$$P_e = P_s - P_d = \text{kW-hours unaccounted for.}$$

And percentage loss is, p per cent. $=(p/P_d)100$.

Because of the relatively small number of consumers per mile of, say, a rural line, it is important that the cost of line construction be kept down to the minimum, consistent with reasonable service. This is the surest way to keep the fixed charges within reason, and it reduces to a minimum the amount which prospective consumers would be asked to contribute toward the cost of a line extension.

The line construction employed, although it must of necessity be reasonable in cost, must at the same time embody all of the features which contribute to make possible safe and continuous operation. The principal features of line construction for a three-phase 3-wire, or a single-phase 2- or 3-wire primary feeder with a 3- or 4-wire secondary main built to offer good service for best economy, would take the following form:

Use of a single wooden pole.

Use of a single wood crossarm for the primary feeder set high up so that the third conductor (when required) can be placed at the top of the pole.

Having horizontal arrangement of the conductors, *i.e.* using one crossarm set as near the top of pole as practicable for the primary conductors.

Using metal or wood braces for the crossarm.

Having one crossarm for the secondary circuit, or, employing a three- or four-spool rack for the secondary main.

At a terminal pole, or at pole where branch-taps lead from the primary feeder, using strain insulators and double crossarms.

Where a pole transformer is located, using double crossarms and transformer supporting irons on the top and bottom crossarm, with switch or cut-out fuses and/or lightning arrester on the top or lower crossarm, whichever is most convenient (see fig. 31).

Employment of transformer secondary neutral earth and lightning-arrester earth, and insulating them from the pole; not joining them together, but earthing the transformer neutral at the adjacent pole. When making the earth see that it is not less than 4 ft. from the pole, as the soil around the pole is more or less soaked in creosote and is of high resistance.

Placing the secondary neutral conductor (for rack construction) either the uppermost or in the centre; for crossarm construction, locating neutral conductor to any one side or in the middle, just as conditions suggest to be best.

Employing the longest span possible, *i.e.* up to about 300 ft.

Using a high strength conductor of satisfactory conductivity, preferably copper-alloy conductors, as such conductors go with a copper-line construction.

In the planning of, and the drawing up of, estimates for rural service, it is necessary to prepare a basis of maps and to provide adequate means for serving the different sections in a manner which will ensure satisfactory service consistent with the investment and other costs. The first step is to determine the extent of the territory or district to be served, that is to say, it is necessary to study:

The district as a whole;
The territory surrounding each of the largest centres considered independently; and
The subdivision of territory into sections.

There are always very good reasons why mapped information of the distribution over a territory should be readily available; one of the chief reasons for much detailed information is that the distribution is spread over a considerable area and never concentrated in one place. Need of such information arises, for instance, when:

Ascertaining whether a line or circuit or the transformer would carry a new or a prospective customer's load;
Interconnecting or extending circuits;
Analysing the most economic lay-out of a circuit, section, or line.

In preparing an economical lay-out of the distribution system, and in recognising the many advantages that come from keeping complete records, it is necessary to have maps and records and a general classification of the whole distribution system.

Despite the fact that the investment in some distribution systems may approach or exceed that in the generation, there are cases where, if asked certain questions as to size of conductor or size and type of transformer for a certain location, no immediate answer could be given.

Again, for the efficient operation of any distribution system a certain minimum amount of circuit, transformer, and pole information is absolutely necessary. This information also can be given to best advantage in the form of maps, the nature of which may vary from a single-line diagram to complicated groups of sectional maps of almost any size, showing everything from the pole locations to the side of the crossarm which carries the circuit, etc. An excellent practice is to provide separate record routines for the poles, transformers, and equipment, the distribution circuits, their character and extent, and so forth.

A topographical survey map, of a convenient scale, of the territory or district should be procured, and upon it should be shown the boundaries of the urban areas (or those areas where overhead lines are permitted), the rural area, and the location of existing and the proposed overhead and all other lines or circuits; proper symbols being used to indicate the character of the different lines or circuits (foreign or otherwise) and service, and the availability for carrying rural distribution circuits, joint occupancy, or making extensions.

In congested sections where the scale of maps is often found too small to describe adequately the information desired, the section or sections in question may be surrounded by a closed line and the information tabulated separately, with a proper reference to the section or sections, as the case may be. In the case of very large area, a saving in time and expense may be effected by making first a general survey of the territory with respect to possible construction costs, consumers, etc., and then taking for detailed study a section large enough to be representative of all conditions.

In laying out rural or certain urban territory, the important initial points are to

> Plan the development along the lines of single-phase service for lighting and small power per consumer;
>
> Plan the route for the circuits to offer the least expense and/or the minimum length;
>
> Plan all pole-line extensions with adequate care and with the final development in mind, or make heavy enough to carry the number and type of circuits ample for a number of years ahead;
>
> Plan the route or routes, having in mind the possibility of future use of public lighting along roads or highways, joint occupancy of lines;
>
> Start a development plan so that, in any particular section, estimates show it would be better and cheaper to develop the whole section at once, not in parts; ascertain at the beginning that everyone is interested, and will interest themselves in facilitating wayleaves and in getting additional consumers, etc., etc.;
>
> Obtain signed wayleaves for main routes and pole-line extensions, so as to facilitate the same construction to serve other future consumers if desired at any time.

The most extensive and important system records are the secondary distribution maps. The primary system map records are much simpler. The latter are usually made on tracing cloth, and a good scale is 1 in. to 300 ft. An important feature is the drawing of street lines and the printing of street names on the reverse side of the tracing from the circuit information. This allows for erasions when bringing the map or maps up to date, without disturbing the permanent map lines. The main features to be shown are the circuit routing, conductor sizes, phase positions, transformer locations (their size and reference numbers), names of large consumers, location of centre of distribution switches and test pillows or boxes, and so forth. Three lines may be used to indicate the three-phase 4-wire circuit and one line for single-phase branches, the neutral being omitted for simplicity, but the conductor size given should cover all four conductors of the three-phase 4-wire circuits. Mile or half-mile circles should preferably be drawn on the map to provide a quick means of showing distances from the sub-station or transforming centre. For the filing system, prints of these maps can be kept on a swinging map-rack or on stands showing a map on the front and back if the territory is very large, changes being noted on these prints and the original tracings brought up to date at regular intervals.

For practically all distribution systems the most important division of the record system consists of the secondary maps; these should give an accurate picture, for the office, of general conditions in the distribution network.

For every lighting transformer having large number of service connections there may, with advantage, be a secondary map, and power transformer banks or polyphase units feeding more than a few consumers may, as desired, be covered in the same manner.

The paper used for secondary maps may be of vellum sheet suitable for making prints from pencil tracings; all of this work should preferably be done in pencil to allow for the necessity of frequent changes and additions. A scale of 1 in. to 100 ft. is a good useful size, and it is found to be a good practical limit in size of a secondary, allowing a maximum voltage drop of 2 per cent. each way from the transformer without going to uneconomical copper sizes.

The secondary map lay-out should include all matters found essential to the office control of the distribution system, and should show all property lines, as these are a great help, to those in the office, in pole location and house numbering and so forth. The load information on the map is usually in the form of an assumed value for average residences and consumers, such that the values assumed allow for a diversity between houses, and, under full-load conditions, give a transformer loading of not greater than about 125 per cent. For marking in, the value allowed a residence or

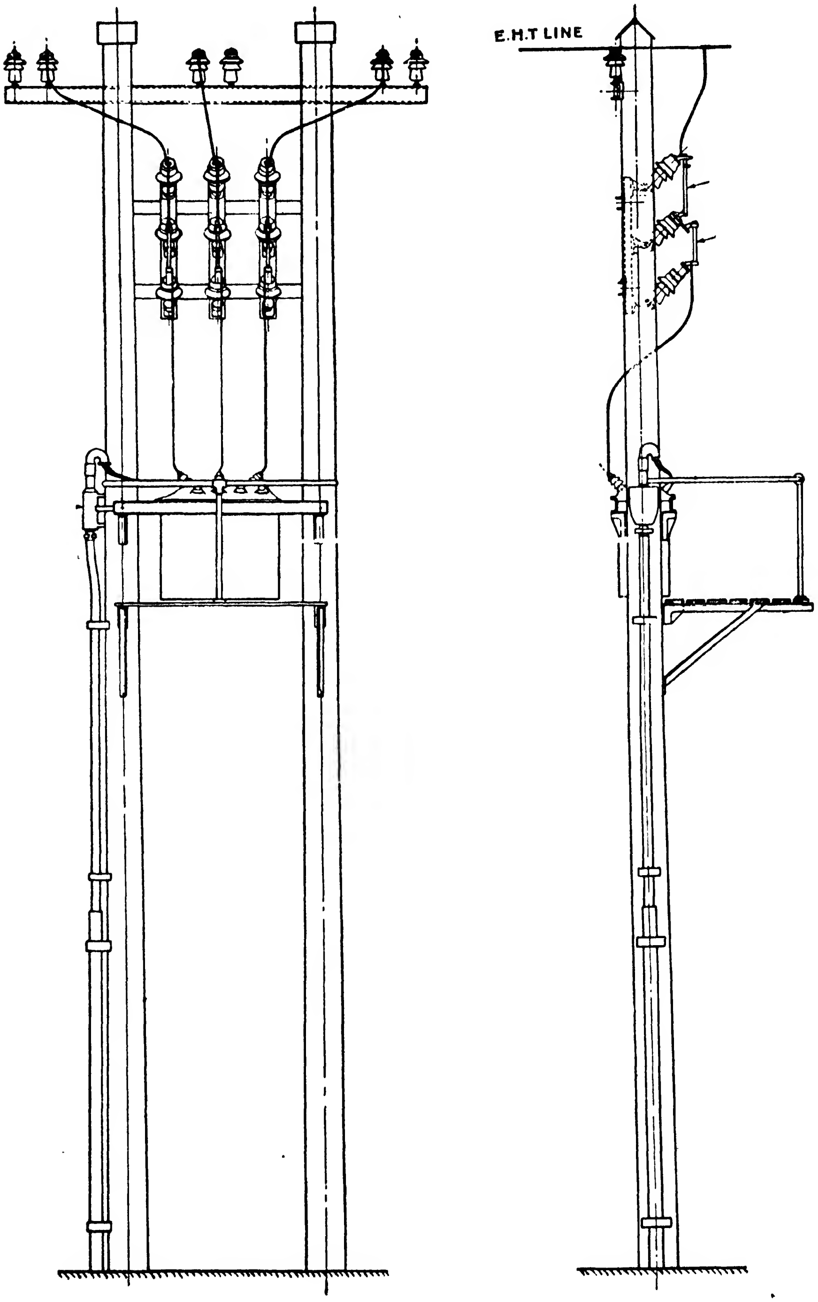


Fig. 43.—Showing distribution or industrial-transformer wood "H" frame installation. (*Henley.*)

other type of load is given in kW directly before or after the street number.

In placing the map over the main sheet covering the whole territory or district, it is necessary to take care to orient its relation to the north arrow, so that adjacent maps on the large sheet can be placed easily and correctly, as it is often convenient to consider a territory several blocks or squares in area in making a study for new or revised secondaries or their extension. For the filing system, these maps, because of their size or their constant use, are filed flat in a drawer, all revisions and additions being made on the originals from time to time and prints taken from them for use.

Transformer records also constitute an important division of the record system. These usually take the form of cards or sheet index. The information recorded on these sheets is principally that of the transformer connection used and the complete nameplate data; the connected load in the case of power consumers is also recorded, as is also the location of the transformer. Where sheets are used, they may be of a convenient size and be kept in a loose-leaf notebook.

Throughout the whole text-matter the author has endeavoured to keep clear of assumptions and probabilities so common in most textbooks; also descriptive matter treating with equipment, protective gear, apparatus, etc. found in manufacturers' catalogues and publications, has been purposely omitted from the text. Manufacturers' publications, which often present excellent descriptive matter dealing with the various methods and schemes and devices for circuit protection, etc. are readily available, and should be on the book-shelves of every electricity undertaking. The whole text-matter concentrates on the most important practical and technical factors always before the operating engineer, it presents knowledge gained by different practical experiences, and it sets forth results based on long years of toil in the construction and operation of large and varied electricity undertakings in various countries.

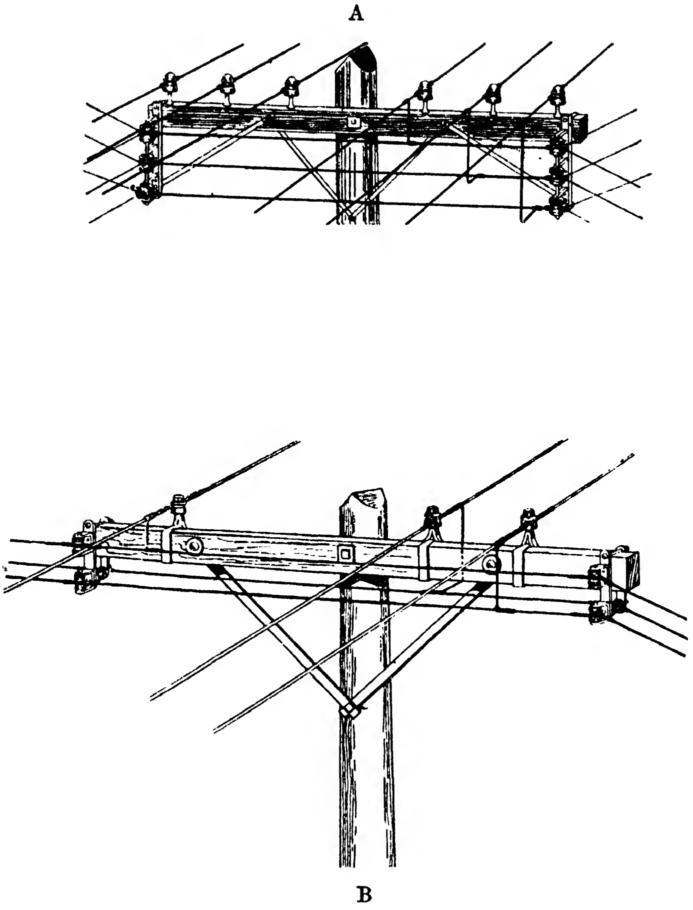


Fig. 44 (A).—Showing combination of crossarm and rack construction for secondary distribution service. The rack provides a method of taking off secondary services from the ends of crossarms. The outside (or inside) conductor may be used as the neutral position.

(B).—Showing crossarm and rack construction where the neutral conductor is placed directly under the crossarm.

Note.—It will be seen that this type of secondary construction permits safer working and climbing space on one side of the pole, *i.e.* on the opposite side of pole to where crossarm is set. Also, the service connections are taken off with pull, from any side, on both ends of the crossarm. *This arrangement offers the shortest pole and least total wind load than any other construction.*

For greater security from broken conductors, which usually occur at the insulator, each conductor can be bridled across the insulator or across a pair of insulators just the same as at a crossing span (referred to on p. 143), that is, by using single conductor (*never* double conductors, which impose double strain and unbalanced loads in the crossing span) with *short* bridle at each single (or double) insulator-support at the pole. For all straight-run crossings (railways, highways, streets, etc.), *single* conductor with *short* bridle at each pole is the simplest, safest and best method of supporting crossing-span conductors or wires.

TABLE XLII.

USEFUL READY REFERENCE VALUES FOR CALCULATING VOLTAGE DROP, LOAD, OR DISTANCE IN MILES OF CIRCUIT FOR THREE-PHASE 3-WIRE DISTRIBUTION LINES.

Size of Conductor in sq. in.	Effective Spacing of Conductors in inches.	Current per Phase in amperes per kVA.	Voltage between any Two Conductors.	Voltage Drop per mile of circuit per kVA transmitted (k).
0·075	36	1·3	440	1·8
"	"	0·26	2,200	0·36
"	"	0·17	3,300	0·241
"	48	0·087	6,600	0·124
"	"	0·052	11,000	0·074
0·100	36	2·6	220	3·1
"	"	1·3	440	1·6
"	"	0·26	2,200	0·31
"	"	0·17	3,300	0·21
"	48	0·087	6,600	0·107
"	"	0·052	11,000	0·064
0·150	36	2·6	220	2·6
"	"	1·3	440	1·3
"	"	0·26	2,200	0·26
"	"	0·17	3,300	0·176
"	48	0·087	6,600	0·092
"	"	0·052	11,000	0·055
0·200	36	2·6	220	2·4
"	"	1·3	440	1·2
"	"	0·26	2,200	0·24
"	"	0·17	3,300	0·16
"	48	0·087	6,600	0·085
"	"	0·052.	11,000	0·051
0·250	36	2·6	220	2·3
"	"	1·3	440	1·2
"	"	0·26	2,200	0·23
"	"	0·17	3,300	0·15
"	48	0·087	6,600	0·081
"	"	0·052	11,000	0·049
0·300	36	2·6	220	2·2
"	"	1·3	440	1·1
"	"	0·26	2,200	0·22
"	"	0·17	3,300	0·15
"	48	0·087	6,600	0·078
"	"	0·052	11,000	0·047
0·400	36	2·6	220	2·1
"	"	1·3	440	1·09
"	"	0·26	2,200	0·21
"	"	0·17	3,300	0·14
"	48	0·087	6,600	0·075
"	"	0·052	11,000	0·045
0·500	36	2·6	220	2·0
"	"	1·3	440	1·0
"	"	0·26	2,200	0·203
"	"	0·17	3,300	0·135
"	48	0·087	6,600	0·072
"	"	0·052	11,000	0·043

Example : It is required to transmit 330 kVA a distance of three miles over a 3,300 volt, 3-phase 3-wire, 0·075 sq. in. copper, 50-cycle circuit conductors of 36-in. effective spacing ; *find the voltage drop.*

Voltage drop$=\text{kVA}\times l\times k=330\times 3\times 0{\cdot}241=239$ volts, or 7 per cent.

Example : How many miles can 330 kVA be transmitted over a 3-phase 3-wire 3,300 volt, 0·075 sq. in. copper, 50-cycle circuit with 36-in. effective spacing of conductors, assuming 7 per cent. volts drop ?

$$l=e/\text{kVA}\times k=239/330\times 0{\cdot}241=3 \text{ miles.}$$

Example : For same conditions, etc., *what load can be delivered ?*

$$\text{kVA}=e/lk=239/3\times 0{\cdot}241=330\text{kVA.}$$

APPENDIX.

OVERHEAD LINE REGULATIONS FOR GREAT BRITAIN.

Interesting changes in the (April, 1928) Regulations issued by the Electricity Commissioners, are :

Present Rules.	Recent Rules.
Conductor Loadings.	
(A) For voltages *not* exceeding 325 volts, a.c. (*see p.* 73), $\frac{3}{16}$-in. ice and 8·0-lb. wind.	For voltages not exceeding 325 volts, a.c., $\frac{1}{4}$-in. ice and 8·0-lb. wind.
(B) For voltages exceeding 325 volts, a.c. (*also see p.* 69), $\frac{3}{8}$-in. ice and 8·0-lb. wind.	For voltages exceeding 325 volts, a.c., $\frac{1}{2}$-in. ice and 8·0-lb. wind.
(*As standard a.c. voltage is* 400/230 *volts, it would greatly facilitate rural development by an increase from* 325 *to* 400.)	
Minimum Height of Conductors.	
Minimum height from 15 ft. to 19 ft. for any voltage up to 66,000 volts (*also see p.* 62).	Minimum height of conductors, 20 ft. at 325 volts and the same height at 66,000 volts ; *see p.* 136.
(*This is based on a temperature of* 122° F. *which, although not strictly correct, is the best.*)	
Maximum Leakage Current.	
Twice the leakage current required to operate the devices which make the line dead.	The leakage current shall not under any conditions exceed one-thousandth part of the maximum supply current (*see p.* 242).
(*The amount of leakage current is therefore left to the particular operating device used, without any stipulation as to its limiting features.*)	
Minimum Size of Conductors.	
0·0201 sq. in. cross-sectional area, for *copper.*	0·0098 sq. in. cross-sectional area.
Weight per Mile of Conductor.	
409 lb.	200 lb.
Actual Breaking Load of Conductor.	
1137 lb.	650 lb.
(*In view of decreased conductor loadings, decreased conductor height, etc., the minimum size permissible has been increased to double.*)	

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