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PRINCIPLES AND APPLICATIONS OF
ELECTRICITY

PART VI—TRANSMISSION OF POWER

SECOND EDITION

MACHINERY'S REFERENCE BOOK NO. 78
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CONTENTS

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CHAPTER I

GENERAL PRINCIPLES OF POWER TRANSMISSION

The term "power transmission" is self-explanatory, referring as it does to the transmission of power, *i. e.*, the development of power at one point and its delivery at some other point more or less distant. There are, however, a number of other expressions which are used in connection with the subject of power transmission and which are not as easily defined, and it is therefore deemed advisable to define such words as force, energy, work, power, efficiency, etc., before dealing specifically with the subject of power transmission by means of electricity.

According to Newton's definition, a force is any cause which tends to move a body from a condition of rest to motion, or from a condition of motion to rest. According to a more modern definition, force is any cause that produces, stops, changes, or tends to produce, stop or change the motion of a body. There are two classes of forces: those which act upon a body from without, and those which act upon a body from within. The first class may be termed external forces, and the second class molecular forces.

When motion is produced by a force against a resistance, work is done. In the popular conception of the meaning of the word "work," a visible result is usually presupposed. In a mechanical sense, however, work is supposed to have been performed whenever certain forces have been active against a resistance. The work, for example, may consist of lifting a body against the resistance of gravity, or of moving a body along a horizontal plane against the resistance of friction; but work is also done if simply the friction within a mechanism is overcome, without any other useful result having been accomplished. Work is commonly measured in foot-pounds. A foot-pound is the amount of work done in lifting one pound a distance of one foot against the force of gravity. According to the metric system, in which the kilogram, a weight equal to 2.2 pounds, and the meter, a distance of 3.28 feet, are the units of weight and length, respectively, a kilogram-meter is the unit of work.

Energy is defined as the power or capacity of doing work, and may be classified as kinetic and potential. Kinetic energy is due to motion, while potential energy is due to the position or inherent condition of a body. A moving body which overcomes resistance displays kinetic energy. The amount of energy it displays depends upon its speed of motion, or velocity, and the resistance to its motion. The potential energy of a body resides in it irrespective of motion, and may be defined as its capacity or possibility for doing work. For example, a body of water at a high elevation enclosed by a dam is not performing work, but it is possessed of potential energy, because it has the possibility or capacity for doing work if released and permitted to fall, under the action of gravity, and to operate some hydraulic machinery during the motion thus resulting. Potential energy is also present in a body thrown in the air at the instant before it commences to fall again. In this latter case the potential energy is rapidly transformed into kinetic energy when the body commences to move downward. It may also be said that potential energy is present in gun-powder and dynamite, because these substances possess a capacity for doing work, although that work is not being performed until, due to certain circumstances, such chemical action takes place which permits the potential energy to change into kinetic energy.

A machine, strictly speaking, should be defined as a device by means of which a force is able to produce an effect or do work. In a majority of cases it is supposed that the machine is doing useful work, that is, work which can be utilized for producing desired effects, although this is not always the case. The whole output of the work of a machine, for example, may be sometimes absorbed by friction, and thus apparently lost, as far as its usefulness for accomplishing a desired effect is concerned. The force applied to a machine is commonly called the power.

A distinction is sometimes made between a machine and a motor. A motor is in some instances regarded as the source of power in a purely mechanical sense; in other words, a motor is a machine which transforms some form of energy into mechanical motion. A broad application of the word energy is here made use of, according to which electricity is a form of energy, and the expanding quality of steam or the explosive possibilities of gas are other forms of it. The machines by means of which the energy of electricity, steam or gas can be transformed so that their respective powers can be utilized for doing useful work are very different from each other; but while the machines and the methods of transformation differ, the mechanical results are alike.

As already stated, a force applied to a machine is commonly called the power. The expression "power" is also used for expressing the amount of work that is being done in a certain period of time. A horsepower, for instance, expresses the rate of work done per minute or per second. It is equal to 33,000 foot-pounds per minute. This means that in order to lift, for example, 1,000 pounds 33 feet in one minute, work to the amount of 33,000 foot-pounds, or one horsepower, must be done in one minute. The element of time must be considered, otherwise the rate at which the work is being done cannot be estimated. The time need not necessarily be a minute. It may be a second, in which case only 1/60 of the power would be required; 33,000 foot-pounds a minute, hence, equals 550 foot-pounds per second. The power, however, is still equal to one horsepower.

The power of steam engines, gas engines or electric motors is rated according to this basis. They are built to produce power at a certain rate per second, or per minute. Commonly the electric motor is rated by the second, while the steam engine is rated by the minute, but if a properly constructed one horsepower electric motor and a one horsepower steam engine are compared with each other, at normal nominal load, it will be found that each produces 33,000 foot-pounds per minute or 550 foot-pounds per second. The voltage and current required for the electrical machine, and the quantity of steam and its pressure required for the steam engine, must vary to produce the different amounts of power, but in both cases, one kind of energy is transformed into another. In the first case the electricity is transformed into magnetism through which a pulling action is developed between the field magnets and the armature of the motor, causing rotation, as indicated in Fig. 1. In the second case steam is expanded in the cylinder of the engine, as indicated in Fig. 2, and while thus expanding, forces the piston forward, and transmits power through the piston-rod and connecting-rod to the crank-shaft. In both cases the power produced can be taken off by belting or other means, so that in both cases the results are the same, although the means employed for producing the results are different.

The efficiency of a device or machine may be expressed as the ratio between the power taken out of the machine and the power sent into

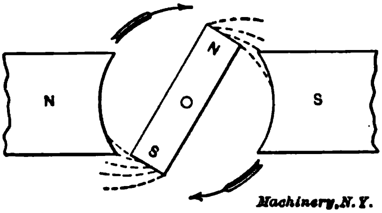

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Fig. 1. Principle of Action of an Electric Motor

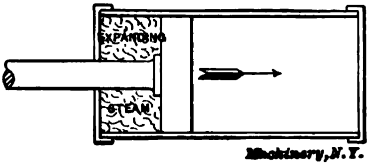

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Fig. 2. Principle of Action of a Steam Engine

the machine. For instance, if an electric motor develops 8 horsepower, that is, if 8 horsepower can be taken off from the belt pulley of the motor and used for driving other machinery, and an amount of electrical energy equal to 10 horsepower has been sent into the motor in the form of electric current, to produce the motion of the motor, then the efficiency would be the ratio of 8 to 10, which equals 0.8 or 80 per cent. In power transmission of whatever kind, whether electrical or purely mechanical, the efficiency is one of the most important features to be considered. The choice of method for power transmission is usually guided entirely by the efficiency expected, and the cost of the various apparatus required.

Methods of Transmitting Power

Although it may be stated as a demonstrated fact that electrical transmission of energy is by far the most efficient method in existence when all factors are taken into consideration, other methods have been tried extensively, and are used to a considerable extent under favorable conditions. Power may be transmitted for certain distances by means of steam, compressed air, water, and wire rope. In large cities, notably in New York, steam pipes extend over considerable distances under the streets of the city. While the steam is used mainly for heating and its utilization for power is very limited in comparison, it may be conceived of that steam for power purposes might be transmitted over small areas in this manner. In Paris a system of pipes carrying compressed air met with general success for some time; in the same way water under pressure can be readily converted into power by means of small water wheels. But these systems cannot be employed for the transmission of power between points widely apart. They represent a case of the distribution of power over short areas.

Wire rope transmission belongs to a class of its own, yet it exemplifies the principle of transmitting power from point to point. A wire rope moving over a distance of several miles cannot, however, be very efficient. The friction, inertia and repairs are very great. It has been estimated that the cable power transmission used for the street car systems some years ago in New York and Chicago barely reached the figure of 20 per cent efficiency; that is, out of over 1,000 horsepower developed, only 200 horsepower were effective in moving the street cars. Hence wire rope transmission is very inefficient, even over comparatively short distances. Over long distances, such as 10 miles or more, the wire rope, compressed air, water or steam methods of power transmission would practically prove commercial as well as engineering failures. Power transmission over long distances is exclusively carried out by means of electricity.

Electric Power Transmission

The transmission of a high-tension direct-current over lines of considerable length is attended with difficulties which present almost unsurmountable objections to its use. The alternating current, instead, seems to be particularly adapted to long distance power transmission. The reasons why the direct-current cannot be employed are, in the first place, cost and difficulty of insulation, and second, the difficulty of transformation. On the other hand, when an alternating current is employed for long distance transmission, the insulation problem is comparatively easy; there is no necessity for revolving parts in the transformers; and the transformation from a high to a low potential or voltage, and *vice versa*, and from an alternating to a direct-current is readily, cheaply and efficiently accomplished. The cost of installation is also much less with alternating current generators than with direct-current generators.

The alternating current employed for long distance power transmission is as a rule not the ordinary single-phase current, but the two- or three-phase current. A two or three-phase current is employed because it makes a properly constructed motor self-starting, which is a condition impossible to accomplish with a single-phase current. The self-starting feature is also of importance when at the end of the transmission line it is desired to change or transform the alternating current into direct-current by means of a rotary converter. These various subjects will be treated more in detail in subsequent chapters.

Efficiency of Transmission

Whether direct or alternating current is employed, the efficiency of the system, that is, the percentage of power returned out of the total power sent into the line, is of the greatest importance. There are a number of considerations which must be taken into account, when the problem of transmitting a given power over a given distance is to be solved. The most important features of the problem are the drop of voltage in the line, the power lost during transmission in the line, the cost of the copper wire employed, and the relation between the cost of the copper and the power lost during transmission.

In order to examine a specific case, let us assume that 100 horsepower are to be transmitted a distance of one mile with a 10 per cent drop in voltage. If the engine delivers 100 brake horsepower and the dynamo transforms, say, 95 per cent of this power into electrical energy, then 95 horsepower will enter the transmission line. Assume that of this 90 per cent will be delivered at the other end of the line. The power delivered then at the distant end of the line will be 95 — 9.5 horsepower, leaving a balance of 85.5 horsepower. The process, however, is not yet completed, although the power is now at hand, ready for use. It is now necessary to transform it again into mechanical energy by means of an electric motor. This transformation involves a loss of from 5 to 10 per cent on an average. Hence the balance left will be 85.5 — 8.55 = 76.95 horsepower with 10 per cent loss in the motor, and 85.5 — 4.275 = 81.225 horsepower at 5 per cent loss in the motor. The efficiency of transmission with a 100 horsepower at the one end, and with the losses throughout in the dynamo, transmission line, and motor taken into account, will thus be about 77 per cent with a 10 per cent loss in the motor. The 100 brake horsepower delivered by the engine is thus reduced to 77 horsepower on account of the electric transmission. This loss is not prohibitive if the cost of the transmission line is within reasonable limits. In some cases, however, the cost of the transmission line becomes very high, sometimes prohibitive, and in such instances certain means must be employed to raise the efficiency or to reduce the cost of installation. It is evident that a high efficiency is profitable or not, according to whether the increased cost of installation, due to the increased efficiency, is proportionately less or greater than the gain in efficiency.

Effect of High Voltage on the Efficiency

When power is lost in the transmission line it is wasted in the form of heat. This loss is commonly called the C^2R loss, and is due to the dissipation of the electrical energy through the resistance. The reason why this loss is termed the C^2R loss is because it equals the square of the current, in amperes, multiplied by the resistance, in ohms. The product obtained is the heat loss in watts. This loss is of a serious character and increases rapidly with any increase of current in the circuit. The relationship between the power loss in the transmission line to the strength of current, in amperes, in the line, is shown in Table I. The figures in this table illustrate the influence of a diminishing current and an increasing resistance upon the losses in the line. The current is shown to diminish systematically, while the voltage increases in the same proportion, so that the total amount of power transmitted is kept constant. The loss of power in heat during the transmission, however, is shown to diminish with a decreasing strength of current, even when the resistance increases. It is thus evident that the losses in transmission are due to the use of a heavy current. One of the axioms, therefore, of electric power transmission is that the current should be kept at a minimum value by the employment of high voltages in the transmission line. As will be seen in Table I, in the first line of figures given, the total drop with 10 ohms resistance and a current of 10 amperes is 100 volts. A loss of 100 volts out of 1,000 is a drop of 10 per cent and at the same time a resistance of 10 ohms causes a waste of 1,000 watts of the total power of 10,000 watts sent through the line. This is a loss of 10 per cent of the total power to be transmitted.

Now suppose a power line one mile in length is to be erected whose total resistance is one ohm. If 10 kilowatts (10,000 watts) are to be transmitted at a voltage which is chosen so as to obtain the most economical results, then the following considerations must be observed: the effect of an increasing pressure—the total amount of power remaining the same and the resistance of the line not varying—will be that of greatly improving the operation of the system. This may well manifest itself in a reduced loss in the transmission, represented both by a smaller drop in voltage and by less loss of power in heat. In the case used as an example, if a power of 10,000 watts were to be transmitted at a pressure of 100 volts, a current of 100 amperes would be required. If the resistance in the line is one ohm, it will be seen that the total energy to be transmitted would be wasted in heat, the waste in heat being equal to the square of the current, in amperes, multiplied by the resistance, or $100^2 \times 1 = 10{,}000$ watts dissipated in heat. This condition would be a case in which the efficiency of the transmission would be 0. A pressure of 100 volts hence would be entirely impossible for transmitting the power mentioned with the given resistance.

TABLE I. LOSS IN HEAT IN POWER TRANSMISSION

Amperes	Volts	Resistance in Ohms	Total Drop in Volts	Loss in Heat in Watts
10	1,000	10	100	1,000
9	1,111	11	99	891
8	1,250	12	96	768
7	1,428	13	91	637
6	1,667	14	84	504
5	2,000	15	75	375
4	2,500	16	64	256
3	3,333	17	51	153
2	5.000	18	36	72
1	10,000	19	19	19

Let, however, the pressure be raised to ten times this value, or to 1,000 volts, the resistance remaining at one ohm. Under these circumstances 10,000 watts would be transmitted with a current of 10 amperes. With one ohm resistance in the line, the drop in voltage would be $10 \times 1 = 10$ volts, and the loss in heat would be $10^2 \times 1 = 100$ watts, that is, the loss in heat and in voltage would be but one per cent. The increase of the voltage to ten times its original value thus had the effect of reducing the heat loss from a total equivalent of 10,000 watts, representing the waste of all the power, to 100 watts or one per cent of the power. In other words raising the pressure to 10 times its value reduced the loss to 0.01 of its value. From this we may formulate the fundamental law that if the resistance of a transmission line remains constant, and the total amount of power to be transmitted also is constant, then if the voltage is increased, the loss due to the transmission is reduced inversely as the square of the voltage. According to this. doubling or tripling the voltage, the total power and line resistance remaining constant, produces a reduction of the heat loss of 1/4 or 1/9, respectively, of its value with the original voltage.

Generating the Power

The fact that a high voltage is necessary in developing power for transmission, that it must be transformed up or down, as the case may be, and that a commutator is absolutely out of the question for voltages beyond a certain point, leads inevitably to the conclusion that the only solution to the power transmission problem is to be found in the application of an alternating current. Here again a difficulty arises of a most important character. The simple alternating current, although readily generated and transformed, is hardly suited to the purposes ultimately held in view, namely, the transformation of electrical into mechanical energy. Recourse is, therefore, as is already mentioned, had to the two-and three-phase alternating current for such purposes.

CHAPTER II

POWER TRANSMISSION PLANT AND APPARATUS

Modern power transmission plants, consist, in general, of an equipment of two or three-phase alternators and step-up transformers, with either water power or steam as the original source of energy. The receiving or distributing end of the system consists of step-down transformers and a rotary converter. If the current is to be distributed simply as an alternating current for power purposes, no rotary converter is necessary. In Fig. 3 a diagrammatical view of a power transmission installation is shown. In the power station the engine, generator, switch-board and step-up transformer are shown. From the power station the current is carried by the line to the transforming sub-station, provided with switch-board, step-down transformer and rotary converter. We will now describe each of these apparatus in detail.

Generators

The generators used in producing alternating current are commonly termed alternators. They can be made of three types. In the first type the armature revolves and the field magnets are stationary. In the second type the field magnets revolve and the armature remains stationary. In the third type, usually called inductor alternators, both field magnets and armature are stationary and iron cores revolve between the armature core and the field magnet poles.

Every alternator is designed to work at a particular frequency. By frequency is meant the number of alternations or changes in the direction of a current in a circuit per second. For example, if a current in an alternating machine changes its direction 200 times per second, it is said to possess 200 alternations per second, or the frequency of the alternator is 200. The higher the frequency is the greater is the drop in voltage, due to inductance, but the smaller are the transformers necessary for changing the voltage from a higher to a lower one, or *vice versa*. The frequency in alternators may be as low as 20 or as high as 200 or more, according to the purpose for which the current is to be used. Arc lighting, for example, requires a frequency which is not less than 40. The numerical value of the frequency is obtained by multiplying the number of revolutions of the alternator per second by the number of pairs of poles. In practice a high frequency is obtained by using multi-polar machines, that is, machines having a great number of poles.

The unfavorable effect of a high frequency upon the capacity of a line to conduct a given amount of energy has led to the adoption of as low a frequency as is consistent with a continuity of flow. The reason why a high frequency influences the capacity of the line adversely is that

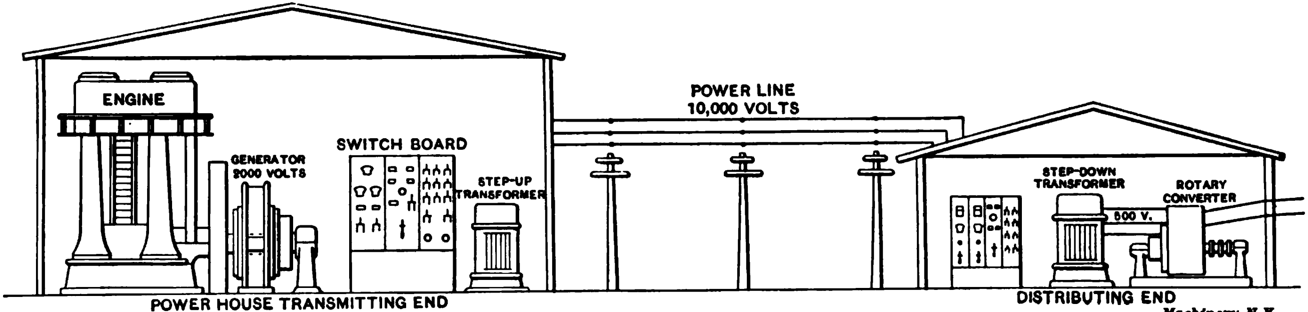

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Fig. 3. General Arrangement of Power Plant and Sub-station

the question of the ohmic resistance of the line becomes secondary in circuits carrying a current of high frequency, the inductive resistance being the limiting influence in all cases where a high frequency is employed. The frequency is generally from 50 to 120 cycles per second, for electric lighting. The effect of increasing the frequency is to make the copper conductor become inoperative. The cross-section of the conductor will not be permeated by the electrical energy. It passes along the outer surface more and more as the frequency is increased, until at very high frequencies a thick copper bar becomes practically non-conductive to the electric current in this form. Low frequencies in power transmission plants are, therefore, necessary features in order to obtain efficient transmission.

General Construction of Single-phase Alternators

All dynamos or generators of electric current produce an alternating current in the coils. Hence the principle of construction of the alternating current dynamo is the same as that of the direct-current dynamo, except that in the latter a commutator is used for changing the alternating current in the armature conductors to a direct-current for the external circuit. In the alternator, a pair of collector rings are substituted for the commutator. These collector rings are connected to the armature winding, and brushes connected to the external circuit are in constant contact with the collector rings.

Alternators are generally compound-wound in order that they may give a constant potential or voltage. Instead of a shunt-winding such as is used on direct-current compound-wound machines, however, a small constant potential direct-current dynamo is used to supply the required current for the field magnets. This small dynamo is sometimes coupled directly to the end of the armature shaft of the alternator, but is more commonly belted to a pulley on that shaft. The series coils of the field magnets of the alternator are excited by a current obtained from the alternator armature, in manner similar to that used in direct-current dynamos, and which has been explained in Part III of this treatise, MACHINERY's Reference Series No. 75. The alternating current cannot, however, be used directly for this purpose, and, therefore, a commutator is employed which changes the alternating current into a direct-current for use in the field magnet windings. This current, while direct, is a pulsating current, that is, the potential rises from a minimum to a maximum value, and then falls again to a minimum; the action is somewhat similar to that of a pump without a pressure chamber.

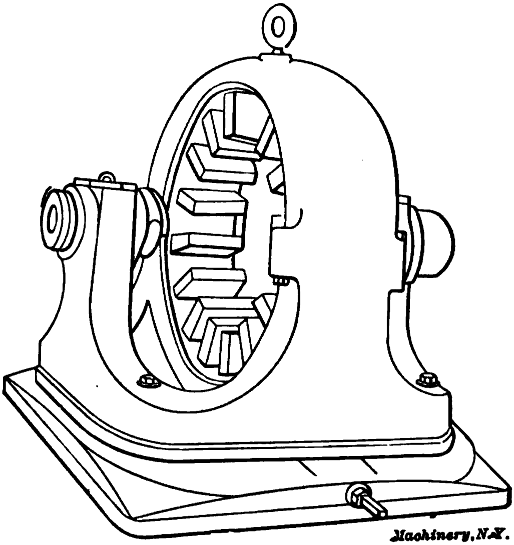

Fig. 4. Frame for a 120 K. W. Single-phase Alternator

The current for the series coils, rectified as described, is now led from the commutator brushes to the field coils, and this arrangement permits of a regulation of the potential of the generator. The regulation of the alternator is thus accomplished as easily as in a direct-current machine. The main energy of the fields, however, is that received from the exciter or small direct-current dynamo already mentioned; only the regulating portion of it is received from the armature itself. This flexible combination of the two methods has made single-phase alternators thus equipped very successful.

The shifting of the brushes on the commutator will be sufficient to meet and correct voltage variations. The brushes may be set when the voltage decreases, or when it rises, or to meet a certain condition of overload otherwise impossible to adequately control. The voltages developed by standard machines run from 1,100 to 2,200 volts, and the alternations are about 16,000 per minute. The fields are made of thin sheet steel, very soft and of high permeability. These sheet steel plates are held in a mold when the frame is being cast. The poles and the frame are thus incorporated with each other as shown in Fig. 4. Joints are avoided by this means and a higher efficiency and better regulation results. The armatures of this class of alternators are slotted and receive a coil very readily, the teeth being cut with parallel sides. The windings are easily held in place by fiber wedges which are removable when examination or repairs to armature coils are necessary.

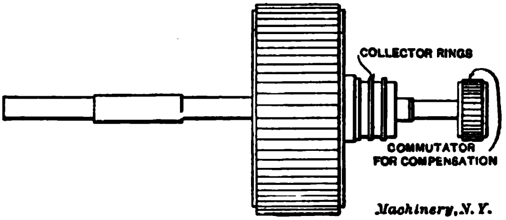

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Fig. 5. Armature for 120 K. W. Single-phase Alternator

TABLE II. DATA FOR 16,000 ALTERNATION SINGLE-PHASE ALTERNATORS

Capacity in Kilowatts	No. of Poles	Belt Speed in Feet per Minute	Weight in Pounds	Revolutions per Minute
45	10	4,607	3,280	1,600
60	12	4,542	4,180	1,335
90	14	4,488	6,480	1,145
120	16	4,450	7,970	1,000

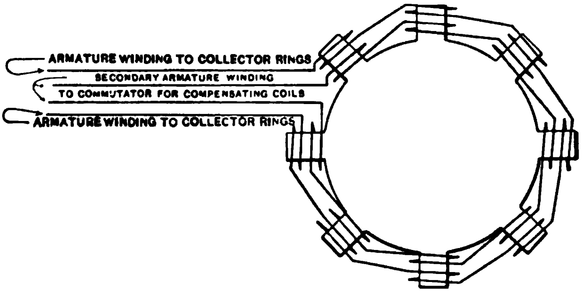

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Fig. 6. Principle of Armature Winding

The field and armature shown in Figs. 4 and 5, are for a 120 K.W. single-phase alternator. The principle of the winding for compensation is shown in Fig. 6. Some data relating to the capacity, speed, number of poles, etc., are given in Table II.

Engine Type Alternators

For large plants where heavy currents are transmitted or distributed at a comparatively high voltage, the flywheel of the engine and the armature cf the single-phase alternator are built in one. The *vis viva* of the armature is sufficient to perform the function of the flywheel proper, without detracting in any way from the efficiency or capacity of the plant. The armatures in this case are built up of a spider upon the rim of which the laminated iron of the armature is secured, as indicated in Fig. 7. A huge flywheel thus results, which serves as an alternator armature. This idea originated in Europe, particularly in Germany and Austria, and is satisfactory as a saver of space and expense. The coils are formed before insertion into the slots. By this means no difficult work is required to make substitutions for injured coils, and only ordinary care is necessary in assembling the armature. The principle is carried out also in a reverse manner, the poles revolving and the armature remaining stationary.

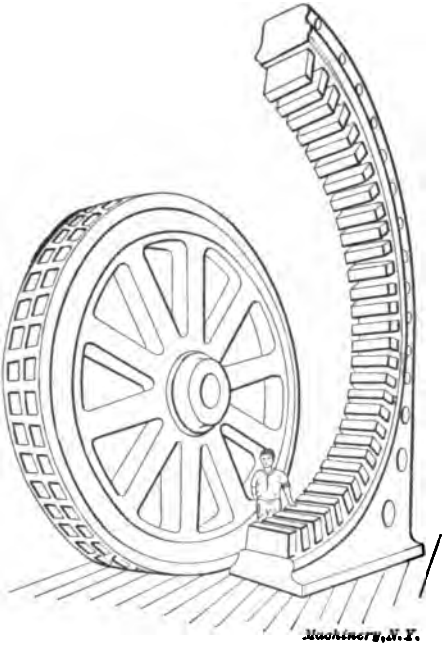


Fig. 7. An Engine-type Generator

TABLE III. DATA FOR ENGINE TYPE ALTERNATORS

Capacity in Kilowatts	Alternations	Revolutions per Minute
300	7,200	130
400	7,200	150
500	7,200	144
750	7,200	90

The gigantic size of large electrical machinery can be best understood by examining Fig. 7, showing the comparative size of an armature and field and a man. The machine in this case represents a 1,500 K.W. generator with an armature of the character described. The armature has not been assembled and the laminations of the armature have not been attached.

Two- and Three-phase Alternators

The type of alternator so far described is the single-phase alternator. As already mentioned, two and three-phase alternating current lends itself, in general, better to the purpose of power transmission. The meaning of the phases of alternating current has been referred to in Part III of this treatise, MACHINERY'S Reference Series No. 75. Briefly, two alternating currents which arrive at different points of their cycles, as their maximum or minimum values, or their point of reversal, at the same moment, are said to be in phase. If, however, one current reaches its maximum value a certain time previous to another current, then the two currents differ in phase. Alternators which are employed for furnishing current which thus has either two or three phases are called two or three-phase alternators, respectively. The separate phases of the current are produced by separate windings of the armature, so arranged as to produce the desired phases. In two-phase machines the difference in phase is one-quarter of a complete cycle. Each armature winding is usually provided with a separate pair of collector rings, making four rings in all. Four wires are also required for carrying the current. Sometimes only three collector rings are used, in which case only three wires are used in the line. In this case one ring is used for each of the armature windings, while the third is common to both. The line wire connected to this common collector ring carries at any moment a current equal to the sum of the currents in the other two wires at that moment.

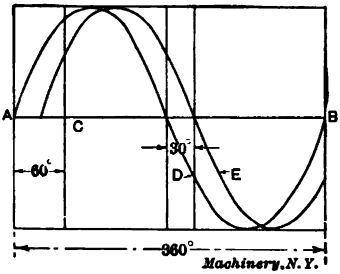


Fig. 8. Graphical Method of Representing Electromotive Force

In the three-phase alternator three distinct windings are used, the difference in phase being one-third of a complete cycle or alternation of the current. In this case the current flowing in one direction is at any instant equal to the current flowing in the opposite direction, so that only three wires are required for the three separate currents. At any moment one of the wires will act as the return conductor for the other two. Only three collector rings are required as well.

When dealing with alternating currents, the graphical method of representing the electromotive force or current, as shown in Fig. 8, is very convenient, as it illustrates to the eye the rise and fall of the electromotive force and the pulsations of the current. As a rule, only one period or cycle is drawn on the diagram, all the cycles being alike. The length of one cycle, as from *A* to *B* is assumed to equal 360 degrees, irrespective of the length of time required for the complete cycle. This method makes it possible to designate different points on the curve as being a certain number of degrees apart. For example, in Fig. 8, if the line *AB* is assumed to be 360 degrees, then the distance from

A to *C* being 1/6 of the total length, *AC* would be 60 degrees. This method of designating various curve points makes it possible to speak of the angle between two curves drawn in the same diagram; for example, the angle between the curve designated as *D* and the curve designated as *E*, would be 30 degrees.

Power Factor

If an alternating electromotive force is applied to a circuit the resulting alternating current may or may not have its changes in direction occuring at the same time as the alternating electromotive force. If the changes of the current take place exactly at the same time as the changes in electromotive force, then the two are said to be in the same phase. If, however, the changes of current occur later than the changes in the electromotive force, then the current is said to lag behind the electromotive force. Should the current change earlier than the electromotive force, then the current would be said to lead the electromotive force. This is shown graphically in Figs. 9 and 10.

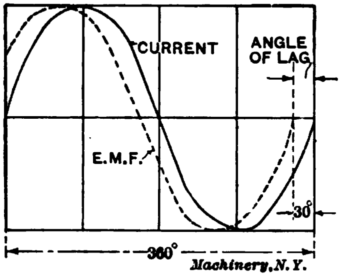


Fig. 9. Current Leads Electromotive Force

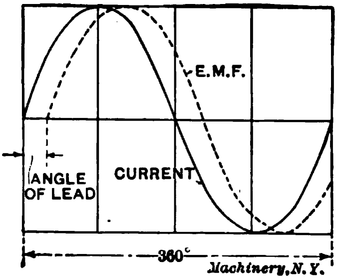


Fig. 10. Current Lags behind Electromotive Force

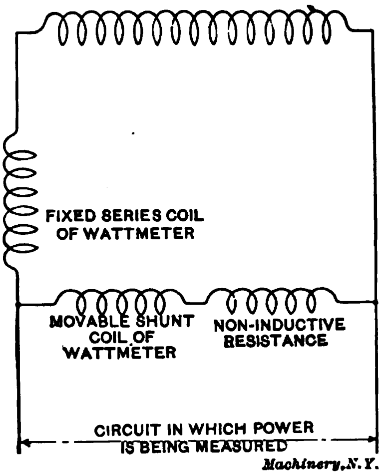


Fig. 11. Diagram showing Principle of Wattmeter

In direct-current transmission the power in watts is determined as the product of the number of volts by the number of amperes in the circuit. In alternating current power transmission this is true only if the current and the electromotive force are in phase, because otherwise the values shown by the voltmeter and ammeter will not be the true values which, if multiplied together, will give the true power. While the power in the circuit at any instant is the product of the actual simultaneous values of current and electromotive force, the product of the volts and amperes indicated by the measuring instruments would not give this true value; the product of the readings of these instruments must be multiplied by a *power factor* in order that the true power may be obtained. This power factor is the ratio of the volt-amperes to the watts, and equals the cosine of the angle of lag or lead of the current. In Fig. 9, for example, this angle is 30 degrees. The power factor depends upon the nature of the circuit and the nature of the machines or resistances in it. A large amount of current may be supplied to a circuit having a low power factor, and yet the actual power given to the circuit may be comparatively low. In a case of this kind the readings of the ammeter are too deceptive to be recorded as an indication of the output of the machine supplying the circuit.

The angle of difference in phase between the current and the electromotive force is called ϕ by general usage, and the formula for the power in watts is:

$$W = E \times C \cos \phi$$

in which

W = power in watts,
E = electromotive force in volts,
C = current in amperes.

It is evident that the greater the angle ϕ, the smaller is the cosine of the angle (that is, the power factor) and the less is the total power obtained from a given current and voltage. Hence a decided difference in phase between current and electromotive force is detrimental to the power output. This difference in phase is due to the inductance and consequent impedance in the line. (See Part I of this treatise, MACHINERY'S Reference Series No. 73).

To show a simple case of the influence of lag on the part of the current, take an instance of 100 volts and 10 amperes operating in the circuit. If there is no difference of phase, the two power components operate simultaneously and the total energy $= 10 \times 100 \times \cos 0° =$ 1,000 watts. If inductance causes a lag of 10 degrees then the total watts $= 10 \times 100 \times \cos 10° = 985$. If the inductance causes a further increase in lag, until it reaches a value equal to 30 degrees, the true watts are $10 \times 100 \times \cos 30° = 866$ watts.

The power factors in these cases are respectively the ratios between the true watts and apparent watts or $1{,}000 \div 1{,}000$, $985 \div 1{,}000$, and $866 \div 1{,}000$. The figures are therefore 1.00, 0.985 and 0.866. The power apparent with ammeter and voltmeter would be 1,000 watts.

The Wattmeter

As already mentioned, power measurements cannot be made by an ammeter and voltmeter for the obvious reason that these instruments take no cognizance of the difference of phase of current and electromotive force. The wattmeter, however, is contrived to meet this requirement and gives readings of the true power in watts. A diagram showing how this device is constructed is shown in Fig. 11. There are, in the wattmeter, a movable coil and a fixed coil. The movable coil is placed as a shunt across the terminals when the meter is used. It has in series with it a non-inductive resistance. The fixed coil is placed in series with the circuit. Under these conditions the instrument has two currents operating in such a manner that the force required to hold the movable circuit with its axis at right angles to that of the fixed coil will be proportional to the product of the mean value of the currents, respectively. This force is indicated by hands on dials on the face of the instrument. The wattmeter gives the net result of the power in the circuit. The conditions required for obtaining successful results, as given by Prof. J. A. Fleming for the operation of a wattmeter, are covered by the following statement: "The current through the series coil of the instrument must have the same value as the current through the circuit to be measured, and the current through the shunt coil of the wattmeter must be exactly in step with the difference of potential between the ends of that shunt circuit; in other words, the shunt circuit must be strictly non-inductive. This can only be secured by winding the movable coil of the wattmeter with no very large number of turns."

Fig. 12. Moderate-speed Revolving-field Alternator

Methods of Driving Alternators

Alternators may be driven from a steam engine or other source of power by being belted to the latter, or they may be direct-connected to the original source of power. This latter method is, perhaps, the most commonly used in modern plants. In Fig. 12 is shown a small moderate-speed revolving-field alternator arranged for being direct-connected to the driving engine. This alternator is provided with a direct-connected exciter for furnishing the current to the field. This particular type is made by the General Electric Co., and may be made for delivering either single-, two-, or three-phase current.

In Fig. 13 is shown a generator direct-connected to a vertical single-cylinder engine. In Fig. 14 a generator is shown direct-connected to a low pressure Curtis steam turbine. In Fig. 15 is shown a gasoline electric generating set of 25 kilowatts capacity of the type made by the General Electric Co.

Fig. 13. Generator Direct-connected to Engine

Transformers

Transformers serve the function of changing the voltage of a current. If the change is from a low voltage to a high voltage, the transformer is termed "step-up" transformer, and if the change is from a high voltage to a low voltage the transformer is termed a "step-down" transformer. One of the features which makes the alternating current especially useful for power transmission is the fact that it readily lends itself to transformation of voltage either up or down. When the electric current has been generated by the alterator and before it enters the power line, all of the energy is let into the transformer to be "stepped-up" to a high voltage, at which it is transmitted through the line. At the end of the power transmission line it passes into another set of transformers before being sent into the distributing lines, and is "stepped-down" to a safe voltage.

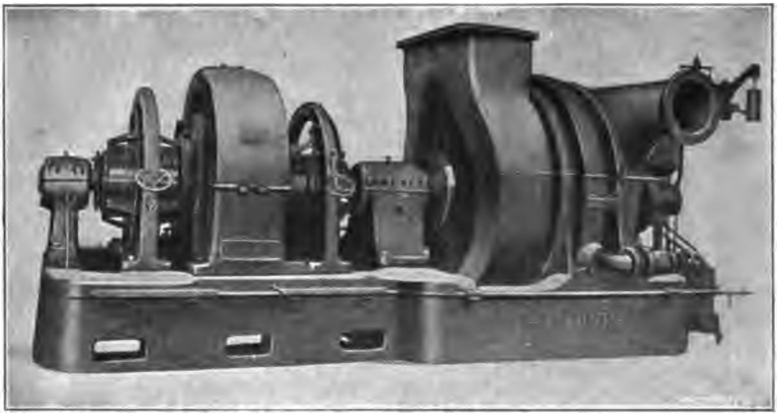


Fig. 14. Generator Direct-connected to Curtis Steam Turbine

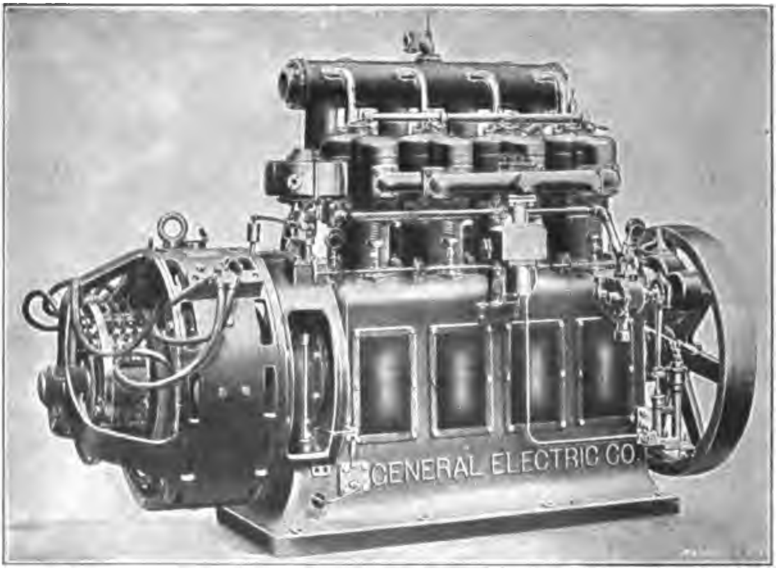
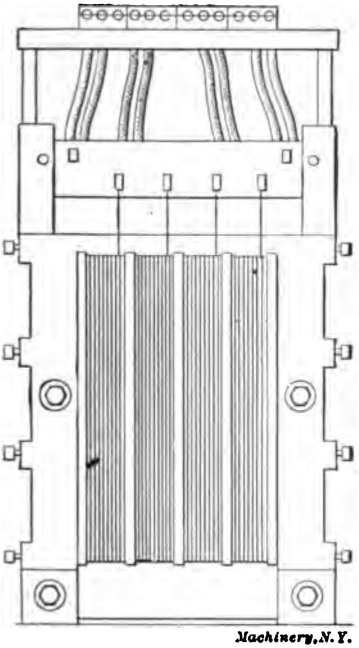


Fig. 15. Gasoline-electric Generating Set

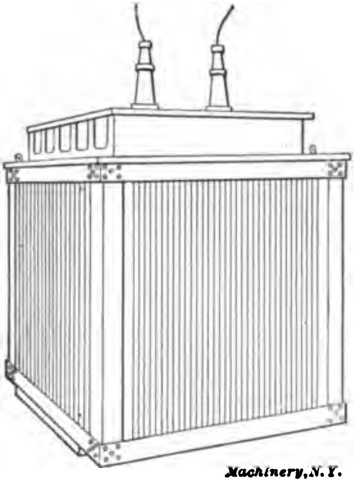
The transformer consists in its simplest form of two coils of wire

wound upon an iron core. One coil is called a *primary* and is supplied with an alternating current at a certain voltage. When this current passes through the primary it causes the iron core enclosed in it to be magnetized and thus generates a current in the other coil, which is called the *secondary*. The current in the secondary may have a voltage greater, equal to, or less than the voltage in the primary coil depending upon the relative number of turns of the two coils. When the voltage is to be raised, the number of turns in the primary must be less than the number of turns of the secondary. The ratio between the number of turns in the two coils is practically the same as the ratio between the two voltages. A step-down transformer, of course, is constructed in a reverse manner; that is the number of turns in the primary must be greater than the number of turns of the secondary. When a transformer is used for either increasing or decreasing the voltage, one of the coils consists of a great number of turns of comparatively small diameter wire, well insulated, through which passes a small current at a high voltage. The other coil, consisting of a few turns, is made of heavy wire, so as to permit the passing of a current of greater strength at low pressure.



Machinery,N.Y.

Fig. 16. General Appearance of Large Size Transformer



Machinery,N.Y.

Fig. 17. Case for Transformer shown in Fig. 16

As an example of the action of a transformer assume that a current of 3,000 volts is to be reduced to 100 volts. The number of turns would then be in the ratio of 30 to 1. The ratio of the voltages is the same as the ratio of the number of turns, because, apart from the inevitable losses in the transformer, the power put into it and that taken out will be practically equal. Assume that we want to take out of the secondary 100 amperes at 100 volts. We then must put into the primary at least 5 amperes at 2000 volts, the product of the number of amperes and volts being the same, or 10,000 in each case.

High Voltage Transformers

The introduction of the polyphase motor of Tesla's design and the development of a high insulation, high-pressure transformer went hand in hand with the sudden augmentation in the number of successful power transmission plants installed. High pressure transformers came into vogue to meet a necessary requirement in transmission plants. They run in sizes from about 10 to over 500 K.W. capacity. The obtaining of high insulation is accomplished by building up both primary and secondary in the form of a series of flat coils of few turns per layer, but many layers, and plunging all into oil. According to the data supplied by the manufacturers of these transformers, the advantages of this construction are as follows:

1.—It divides the total electromotive force between several coils, reducing proportionately the strain within an individual coil.

2.—It divides the electromotive force in a single coil between many layers, thus reducing the potential between adjacent layers.

3.—It enables the coils to be spread apart at the ends so that a very large surface is exposed to the oil, thus providing ample radiating facilities and most thoroughly insulating the bent part of the coils.

4.—The regulation of the transformer is greatly improved.

5.—The windings may be connected in series or in multiple, giving a wide range in electromotive force.

6.—In case of damage tc a coil, another one may be substituted without trouble, and without returning the transformer to the shop.

The use of oil is admitted to be the solution of the insulation problem when discretion is employed in the design of the coils themselves. It insulates, and also conducts away excess heat very rapidly. The difficulty of handling 30,000 volt transformers is self-evident in case of temporary injury or overload. The construction therefore must be of the best character to preserve its integrity under the strain of heavy service. The development of heat arising from the copper wire can be limited by designing the coil to have a small C^2R loss. The heat due to hysteresis and eddy currents in the core, that is, useless currents produced in the core by the currents flowing around it, can only be controlled by fine lamination and the use of a very high grade of soft iron. The iron has been shown to deteriorate through use and become in a sense inefficient. It takes more energy to magnetize it under these conditions than iron which a test has demonstrated to be free from this phenomenon. To prepare iron for use in transformers a special treatment is necessary. Neglect of this will lead to a heavy waste of energy in the transformer a short time after being put into service. Curves showing the relationship between efficiency and load will indicate the rapid rise in efficiency with a relatively light load. They also serve to show the tendency to rise or fall in efficiency with an increasing load up to the full 100 per cent capacity.*

A transformer of large size, though efficient, will waste a great deal of energy, which appearing as heat, must be disposed of A 100 K.W. transformer, for instance, wastes 5 per cent or 5 K.W. This amount of heat will act destructively upon the transformer in the course of time and seriously affect its life. Radiating ribs are therefore supplied to the containing vessel or case, facilitating the radiation of the heat. Corrugations are also employed to increase the surface for the same purpose. High pressure, self-cooling transformers for heavy service are now employed extensively on two and three-phase lines as well as for single-phase. In Fig. 16 is shown the general appearance of a transformer of large size, and in Fig. 17 the case for this transformer. Fig. 18 shows a General Electric transformer for high voltage.

Fig. 18. Transformer for High Voltage

Two additional cases arise in power transmission plants: First, where two-phase currents are to be transformed into three-phase, and three-phase into two-phase, and second, where the employment of transformers in connection with rotary converters is necessary for the special purpose of meeting voltage changes without difficulty. In this latter case, the call for changes of voltage in the direct-current would necessarily mean proportionate changes in the alternating current. A transformer with a means of changing the ratio of the primary and secondary winding covers this situation successfully. By bringing connections out from the various sections of the transformer to an index and dial, regulation in this respect is readily secured.

Transformers for producing potentials of from 100,000 to 150,000 volts are used for obtaining the high pressure required for testing insulating materials for high voltages. These transformers are built along lines similar to those outlined in the foregoing paragraphs.

Rotary Converters

The rotary converter is used principally for transforming an alternating current used in the transmission of power over long distances into direct-current for use in the distributing lines The rotary converter is similar in construction to a direct-current dynamo. The construction is briefly as follows: On one end of the armature shaft a commutator is mounted and on the other end a number of collecting rings, that is, rings used for collecting the impulses of alternating current. These rings are connected to points at an equal distance apart in the armature winding. Hence the armature of the rotary converter is provided with a commutator the same as a direct-current generator, and with collecting rings the same as an alternating current generator or alternator. Brushes are provided, bearing against the commutator on the one side and against the collecting rings on the other side. When alternating current is received at the collecting rings it will cause the armature to turn when brought up to speed. The converter becomes, in fact, what is called a synchronous motor, a machine which will be described later. Direct-current can now be obtained at the commutator end.

This is the most common use for the rotary converter, but it may be stated that the rotary converter is, perhaps, the most flexible and adaptable of all electrical machines. It may be used in at least nine distinct ways. Supplied with alternating current it will deliver direct current as just described. Supplied with direct current it will deliver alternating current. Supplied with alternating current it will operate as a simple synchronous motor. Supplied with direct current it will operate as a direct current motor. If driven by mechanical power it can be made to deliver either direct current or alternating current, and it is possible to have it deliver current of both kinds at the same time. The reverse of this is also possible. If supplied with alternating current it may run as a motor delivering mechanical power, and at the same time deliver a direct current from its commutator, and if supplied with direct current it may run as a motor delivering mechanical power and at the same time deliver an alternating current.

Ordinarily, however, the standard type of rotary converter is not built to receive or transmit mechanical power, but is designed to be used strictly as a transformer or converter of electrical energy, that is, for transforming alternating current into direct current, or direct current into alternating current. In the case when the rotary converter is used for receiving alternating current and delivering direct current, it is usual practice to extend the shaft carrying the armature of the rotary converter so that on the same shaft may be mounted a small induction motor for starting purposes. The induction motor will be referred to in detail later. When the rotary converter is employed for transforming direct current into alternating current a small starting exciter may be required on the extension of the armature shaft.

Three methods may be used for starting rotary converters transforming alternating current into direct current. They may be started under the same conditions as a synchronous motor. This motor, as has already been mentioned, develops a satisfactory torque only after having been brought up to normal speed. For this reason the method of starting the rotary converter by connecting it to the alternating current circuit is objectionable, although feasible, because it requires a large current from the mains which may affect the running of other apparatus connected to the same circuit. Hence self-starting rotaries are permissible only when the capacity of the converter is small compared with the total capacity of the generating plant.

The second method for starting a rotary converter of the class mentioned is to connect it to a direct-current circuit, starting it as a direct-current motor, and then, when it has reached a speed corresponding to synchronism, to connect it to the alternating current circuit. This method is preferable to the first one, but the third method which is very satisfactory and the most usual one, is to start the rotary converter by means of an induction motor which is mounted on the same shaft as the armature of the converter, as already mentioned. When the rotor of the converter has been brought up to synchronous speed by this method it may be connected to the alternating current circuit. This method possesses several advantages, the most important one of which is that the only demand for current from the circuit is that occasionally required for the small induction motor.

One of the advantages of the rotary converter is that when properly designed it will maintain a practically uniform voltage, and is not liable to produce such drops in voltage as usually occur when current is supplied direct from a generator and the load increases. This permits a practically constant voltage to be maintained in the circuits supplied by a generator independent of the variations in load on the circuit supplied from the converter.

Alternating Current Rotaries for Polyphase Circuits

The transmission of electrical energy over great distances has developed with the increasing perfection and adaptability of the rotary converter. A power station, situated at a distant point, may by this means distribute its power with relatively great economy over an area beyond vision from its site. Certain standard voltages and frequencies are employed, as follows: Alternations 3,000, 3,600 and 7,200 per minute, corresponding to voltages of 125, 250 or 550 volts as required. The Standard Westinghouse two-phase rotaries, according to their bulletin, receive at their collector rings, about 0.7 of the voltage given out at the commutator as a direct current. With a three-phase rotary at the collector rings, the ratio is about 0.6 of that given out at the commutator end. Sparking is almost entirely absent from this class of machines and changes in speed are in strict proportion to the frequency of the current from the central station. The result of too swift variations in frequency causes "hunting" or pulsatory movement due to more rapid changes in frequency than can be responded to by the rotary. Fig. 19 shows an illustration of a rotary converter as made by the General Electric Company.

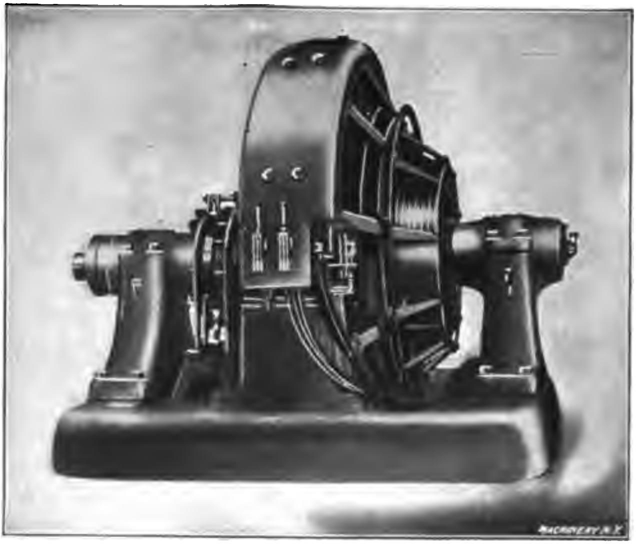


Fig. 19. Rotary Converter

Synchronism

When two alternators run at exactly the same frequency and have the same voltage, they are said to be in synchronism with each other. When alternators are used, for example, for lighting circuits, it is necessary to run them in parallel with each other, and before this can be done without disturbing the voltage, they must be synchronized, that is, must be run so as to have exactly the same frequency, the same voltage and be "in step." In order to determine that the alternators run in synchrony with each other, a device called a synchronizer is used. Various types of these devices are employed. In Fig. 20 a diagrammatical sketch of one type of synchronizer is shown. This synchronizer consists of a transformer with two primaries and one secondary. One primary is connected to the current supplied from the first alternator, and the other primary is connected to the alternator that is to be switched in, that is, the alternator which is to run in parallel with the first alternator for supplying the current to the same circuit. The secondary of the synchronizer has a lamp placed in series as shown in the illustration. When the speed or frequency and the voltage of the alternator to be thrown in are right, then, if the two voltages are not in phase, the effect will be a blinking of the lamp on the synchronizer. By gradually adjusting the speed of the machine to be thrown into synchrony, it is brought very nearly into synchrony, that is, several seconds may elapse between the periods of maximum and minimum brightness of the lamp. At the moment when the lamp has a maximum brightness, and the voltage is the same, the switch is closed and the lamp now glows steadily, showing synchronism.

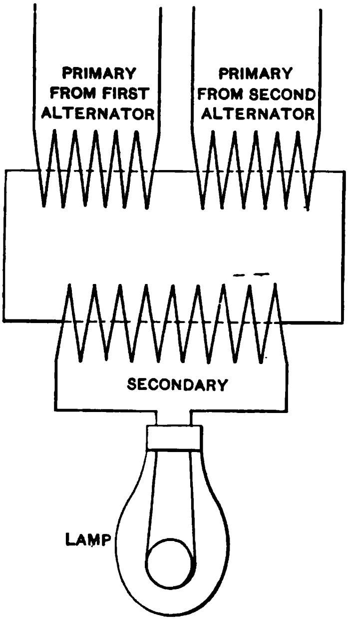


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Fig. 20. Diagrammatical View of one Type of Synchronizer

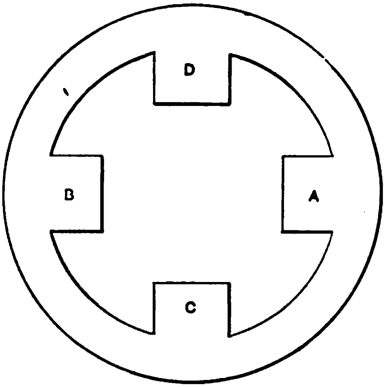

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Fig. 21. Diagrammatical View showing the Means for Obtaining a Rotating Magnetic Field

Motors for Alternating Current

Motors for alternating currents may be of two kinds, either synchronous or induction motors. A direct-current generator will run as a motor when it is supplied with direct current, but an alternator will not run as a motor or drive another alternator as a motor unless the two machines in series are working in synchronism, or, as just explained, are running in exact accord as regards the varying phase or alternations of the current. For example, if we have two single-phase alternators of the same kind and type, and one is driven as a generator, the other can be driven as a motor, providing it is first run up to such a speed that its alternations are exactly the same as those of the alternator running as a generator. If at the time when the two machines run at the same speed, the one running as a motor is connected to the circuit of the one running as a generator, then it will continue to run without being thrown out of synchronism. Hence a synchronous motor may be defined as one which has its field magnets excited by a direct current, its armature fed by an alternating current, and which must be started by some exterior means, until it has the same speed as the generator supplying current to it. Hence it is not a self-starting motor, with a single-phase current. With two- and three-phase currents it is possible, however, to produce such effects that a motor will start and run up to speed, and run under load in perfect synchronism with the supply. Such a motor is called an induction motor.

Synchronous Motors

As has already been mentioned, any alternator may be used as a motor, provided it be brought into synchronism with the generator supplying the current to it. The method of bringing an alternating current motor into synchronism with the generator is similar to the operation of bringing two generators into parallel. The field must be supplied with direct current and the field circuit left open until the machine is in phase with the generator. In case the number of poles of the motor is the same as the number of poles of the generator, then the two will, of course, run at the same speed when in synchronism. But if the number of poles of the motor is different, the speed of the motor will be equal to the speed of the generator multiplied by the ratio of the number of poles of the motor to that of the generator.

While two- and three-phase synchronous motors may be made self-starting, it is considered better practice to bring the machines up to speed by independent means, before supplying the current. The machines may be started by a small induction motor, the load on the synchronous motor being thrown off, or the field may be excited by a small direct-current generator belted to the motor. This generator is then used as a motor for starting the machine. Current to run it is frequently taken from a storage battery. The load has an important effect in the operation of synchronous motors. If such a motor is properly regulated as to the load, its power factor will equal 1, but if the load varies, then the current in the motor will either lead or lag behind the electromotive force, and the power factor will vary accordingly. If the motor should be so overloaded that there is a decrease of speed, then it will immediately fall out of step with the generator and stop. One method used for obtaining a power factor nearly approaching 1 is to use a synchronous motor on the same circuit with an induction motor. By increasing the field of excitation, the synchronous motor in this case may be made to have a current which leads the electromotive force, while the induction motor will cause a lag. The two effects will thus tend to neutralize or balance each other, with the effect that the power factor will approach 1. Synchronous motors are not satisfactory when the required speed is variable, or the load changeable. They are used to best advantage for large units of power at high voltages when the load and the speed are constant. The disadvantages of the synchronous motor are its inability to start under load and the necessity of direct-current excitation.

Induction Motors

An electromagnet which is supplied with alternating current produces an alternating field which varies in intensity from a maximum in one direction to a maximum in the opposite direction. If two electromagnets are so placed that they act at right angles upon the same air space and if they are both supplied with alternating current of the same phase and periodicity, the two magnets will produce an alternating field which is the resultant of the two fields due to each magnet separately. Now if the phase of the current in the two electromagnets is different, the other conditions being the same for each, then a so-called rotating field will result which will vary its direction continuously and which may be made to retain a uniform strength. This rotating field is the principle upon which the use of the induction motor, which will be described in the following, is based.

The production of a rotating magnetic field may be explained by referring to Fig. 21. In this illustration *A*, *B*, *C* and *D* are the poles of an induction motor, *A* and *B* being one pair wound from one pair of wires of a two-phase alternating circuit, while *C* and *D* are wound with the other pair of wires, the two phases being 90 degrees apart. At a given instance *A* and *B* will receive the maximum current, making *A* a north pole and *B* a south pole. At this moment *C* and *D* are demagnetized and the magnetic field is directed in the direction from *B* to *A*. As the cycle of the current progresses, the magnetic flux at *A* decreases, while that at *C* increases, so that the magnetic field is moving or rotating in a clock-wise direction towards *C*. It will be seen that a complete rotation of the field is performed during each complete cycle of the current, and if an armature is placed within the poles it will be caused to rotate simply by the shifting of the magnetic field, without the need of using any collector ring on the armature, or supplying it with current from an outside source. It should be noted that the expression *rotating magnetic field* refers to the magnetic condition within the poles, and that this expression must be distinguished from the expression *revolving field*, which refers to the mechanical operation of the part of the machine containing the field magnets.

In an induction motor that portion of the machine to which current is supplied from an outside circuit is termed the field or the primary. That portion of the machine in which currents are induced by the rotating magnetic field is termed the armature or secondary. Either the primary or the secondary may be the revolving part. In the more modern machines the armature or secondary revolves.

A common type of armature is that known as the "squirrel-cage" type, which consists of a number of copper bars placed on an armature core and insulated from it. On each end the bars are connected by means of a copper ring. In all induction motors the field windings are so arranged that a number of pairs of poles are produced. This is a necessary requirement in order to bring the speed of the rotating field and the rotor down to a practical limit. If, for example, only one pair of poles were employed, then with a frequency of 60, the revolutions per minute of the rotating magnetic field would be 3600.

It should be noted that the rotor or revolving part of an induction motor does not revolve as fast as the rotating magnetic field, except in cases where there is no load on the motor. When loaded, there is a slip between the rotating field and the rotor, this slip being necessary in order that the lines of force of the magnets may cut the conductors in the rotor, and thus induce currents without which motion would not take place. Another fact to be noted in connection with the induction motor is that the current required for starting the motor under full load is from 7 to 8 times as great as the current for running the motor under full load. Induction motors should be run at as near their normal primary electromotive force as possible, because the output and the torque are directly proportional to the square of the primary pressure. As an example may be mentioned that a machine which will carry an overload of 50 per cent at a normal electromotive force, will hardly carry its full load at 80 per cent of the normal electromotive force.

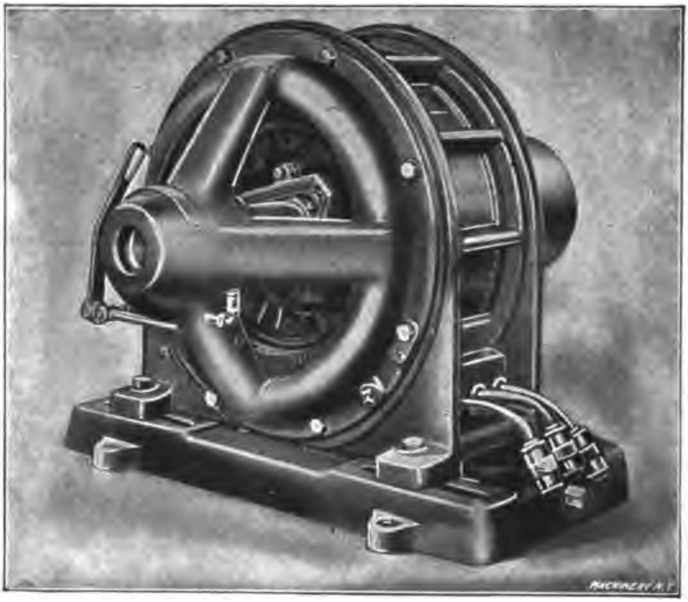


Fig. 22. Induction Motor

From the description of the construction of the induction motor it is apparent that it is an electric motor whose action depends upon the induction of an electric current in the armature. The alternating current in the field magnets induces currents in the windings of the armature, and these induced currents produce electro-magnetism in the core of the armature. The fact that the electro-magnetism in the armature is due solely to induction is the reason for the name of the motor. The windings on the armature are connected in parallel and are, so to speak, short-circuited, that is, they have no connection with any outside circuit. An induction motor is frequently termed an asynchronous motor. In Fig. 22 is shown an induction motor made by the Sprague Electric Co.; this motor is of 50 horse power capacity.

Single-phase Induction Motors

A single-phase alternating current produces an alternating and not a rotating magnetic field, as has already been mentioned. If, however, the rotor or armature of a single-phase motor is made to rotate rapidly while the stator or field is supplied with an alternating current, the currents induced in the rotor conductors will themselves produce a magnetic field, and since this field will be out of phase with the primary field, the two magnetic fields, due to the stator and rotor, will together form a rotating field, and the action of the motor will then resemble that of a two-phase motor. In order, however, to get the rotor to revolve in the first place, a special device which generally takes the form of an auxiliary winding supplied with current through a resistance giving it a difference in phase from the main current, is employed. This auxiliary winding is switched out when the rotor has attained sufficient speed.

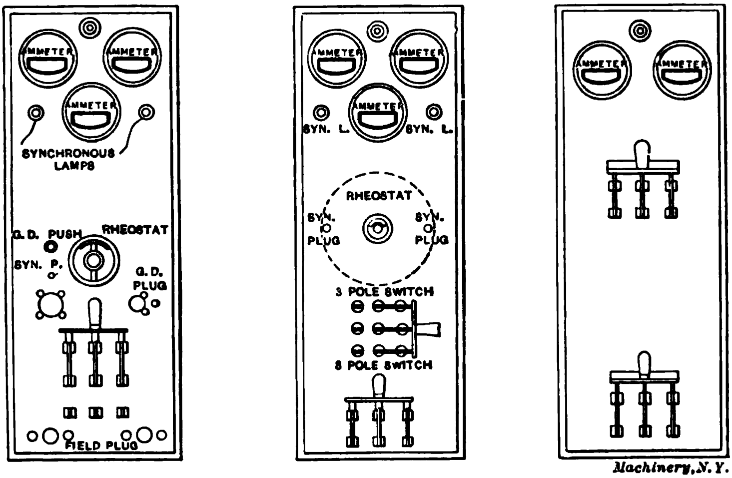
Switchboards

The switchboard has been aptly described as the heart of an electric power generating station. All the currents generated by the various electrical machines are led to it, and from it radiate all the lines through which the electrical current is distributed. There are a great number of types of switchboards, and it is not possible to describe them in any but a general way.

The purpose of the switchboard is to concentrate or centralize the means of controlling the energy developed in a power station, and it provides means for controlling, distributing, and measuring the current; it offers, as well, a means of protection against injury to the apparatus. The switchboard should be so located that the person or persons in charge of the plant may have a full view of the machines and the switchboard at the same time. The switchboard should also be located so that the connections between the machines and the board may be as short as possible. Sufficient space should be left back of the board so that the operator can easily and safely inspect, repair and adjust the connections, which are made on the back.

Switchboards usually consist of several slabs or panels of marble or slate, on the one side of which are placed the various instruments, handles and switches for the operation of apparatus, and on the other side of which the connections to the apparatus in the power station are made. The sections or panels are each about 2 feet wide and from 6 to 8 feet high. A separate panel is used for each of the various apparatus in the station. There are, for example, generator panels, feeder panels, rotary converter panels, motor panels, etc. A complete switchboard built up of a number of these panels is held together by means of a frame consisting of a rectangular iron support resting on more or less ornamental legs. There is usually an open space of about two feet between the floor and the lower part of the frame, which supports the panel. The construction of the panels is usually such that extra panels can be added as required.

The reason why marble is used for the panel is on account of the necessity of using a strong insulating and fire-proof material. Slate may be used instead of marble for circuits which are not above 1000 volts. If slate is used for circuits over 1000 volts, the sections of the circuits which carry the high potential current must be insulated from the panel. The reason for this is that slate is liable to contain veins of lower insulating materials. Marble panels are left in their natural white state, whereas slate panels are finished in oil or black enamel. The black oil finished slate panel gives a neat appearance, and harmonizes with the finish of the devices mounted upon it. Marble, however, is stronger, and as already mentioned, is a much better insulator than slate, but on account of the fact that its polished surface will show oil stains, it is more difficult to keep it looking clean and neat. Sometimes marble panels are black enamelled for this reason, and then present a dull black finish.

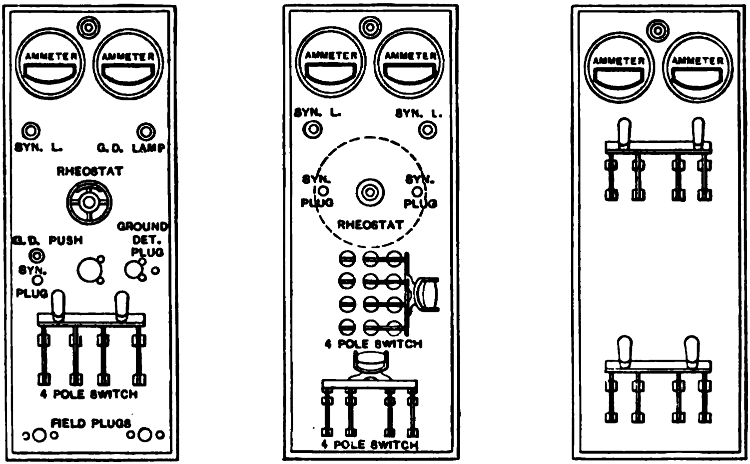


Machinery,N.Y.

Fig. 23. Various Arrangements of Switchboard Panels

When the instruments which are to be used on the switchboard are mounted on it, similar instruments and devices on the different panels standing side by side should be located at the same height, as this tends to give the panels a symmetrical and pleasing appearance. The instruments that are mounted on the switchboards are, as a rule, as follows: Indicating voltmeters, field ammeters, swinging voltmeters, switches, rheostats, synchronizers, ground detectors, fuses, circuit breakers, transformers, compensators, and wattmeters.

The general arrangement of the various instruments on the switchboard is generally as follows: Circuit breakers and fuses are placed near the top of the panel; the reason for this is that if any arc should rise, no injury will be done to the adjacent devices or to the operator. Beneath the circuit breakers are located the various volt- and ammeters. About the middle of the panel are placed the hand-wheel for operating the rheostat, the field switches, etc., as well as the large recording wattmeters. Of course, this arrangement is often departed from. A further description of switchboards will contain little more than a description of the various apparatus which it carries. The types of switchboards used in different stations vary greatly, so that only general statements can be made relating to their arrangement and design. In Figs. 23 and 24 are shown various arrangements of switchboard panels, and Fig. 25 shows the general appearance of a switchboard for an alternating current installation.



Machinery,N.Y.

Fig. 24. Various Arrangements of Switchboard Panels

The importance of the switchboard is realized when it is remembered that it offers a check upon the efficiency and economy of the whole power installation. All the machines have been designed to operate most economically under certain loads, and the switchboard provides the indicating and recording instruments by means of which it becomes possible to determine if the machines are working under the most advantageous conditions. A record can also be kept of the total output. The protecting devices contained on the switchboard are also of importance in that they prevent injury and economical losses due to unforeseen causes. It is highly important that these safety appliances are kept in proper repair so that they are always reliable, especially when they are of the automatic type. If they are not kept in good condition they may be a greater source of danger than of benefit, because the operator will naturally rely upon them, and hence invite difficulties which otherwise might have been guarded against.

Instruments Used on the Switchboard

Voltmeters are employed for the purpose of enabling the switchboard attendant to obtain the voltage of any section of the system, or of any generator, by the use of a plug switch inserted in a voltmeter receptacle. Swinging voltmeters are mounted on an arm attached to a bracket fastened to the side of the panel and can be swung back and forth. The mounting is similar to that of the synchronism indicator shown in Fig. 26. When a second generator panel is installed for the purpose of operating more machines in multiple, the use of another

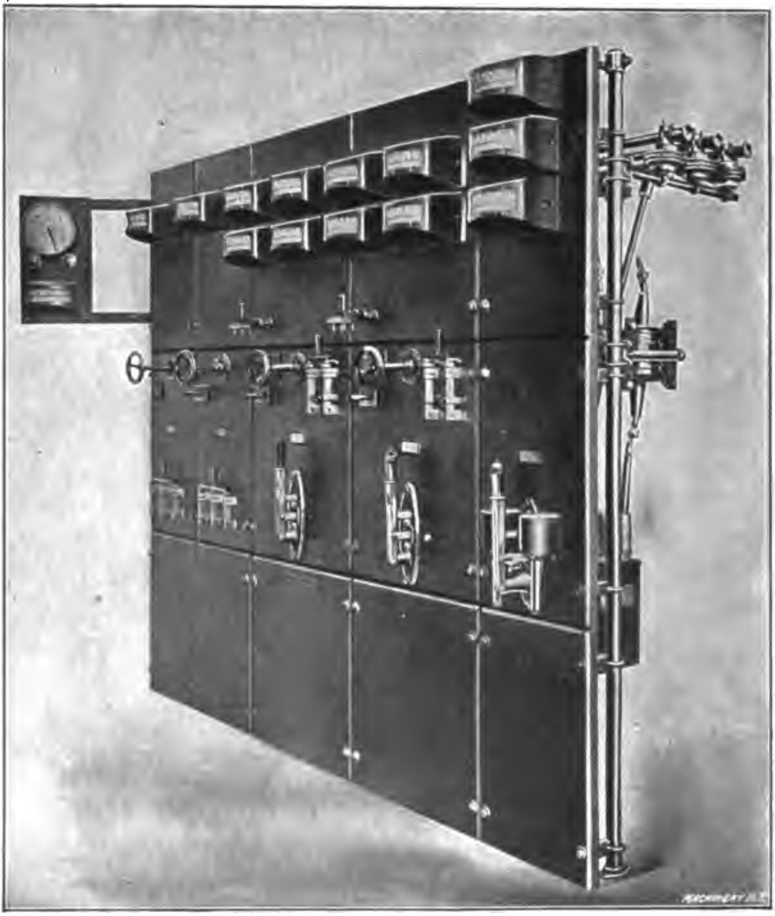


Fig. 25. A Complete Switchboard

voltmeter becomes necessary, and this voltmeter is then mounted on the swinging arm so as to occupy a place beside the first. The two voltmeters can thus be easily compared, and any differences in voltage between the two generators seen at a glance. Ammeters are used for measuring the current and are mounted on the switchboard, the same as the voltmeters. The general appearance of the ammeter and voltmeter is practically the same.

Switches are used for making or breaking contacts so as to connect and disconnect one part of a circuit with another. It is evident that switches are required to act quickly, as the time for making the contact and the abruptness in breaking the contact are matters of great importance.

The rheostat is often mounted on the back of the generator panel or in proximity to it. There are two rheostats for alternating current machines, one for the exciter and the other for the generator. Hand-wheels are mounted on the face of the panel, which are employed for turning the contacts. These latter do not appear on the front side of the panel; only a dial with a movable index is seen on this side. The dial index shows the relative value of the resistance when the rheostat is operated by the hand-wheel. In some instances the rheostat is placed at a point some distance from the switchboard, in which case only the dial with its various connections and the hand-wheel are placed on the panel.

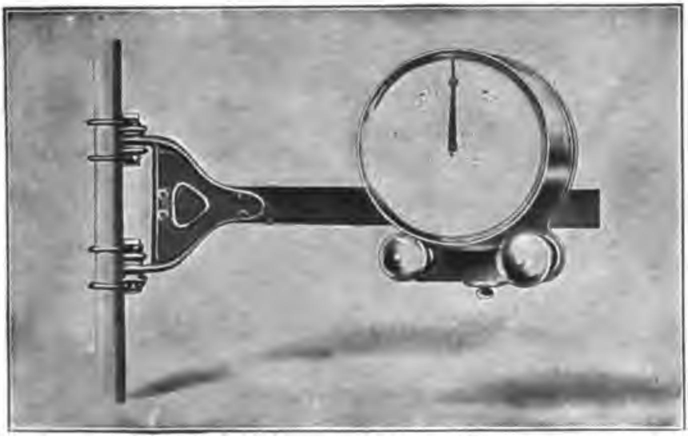


Fig. 26. Synchronism Indicator

Synchronism Indicator

The method of bringing two alternators into synchronism by means of an electric lamp has already been referred to. Any satisfactory device used for synchronizing two or more alternating current machines should properly perform three distinct functions. It should indicate whether the starting machine is rotating slower or faster than the other machine; it should indicate the amount of difference in speed;

and it should accurately indicate the moment when synchronism and coincidence in phase of the two machines occur. A synchronizing lamp does not perform the first function. It performs the second function properly, and the third function only approximately. For this reason special instruments called synchronism indicators have been brought out. The pointers on these instruments move around a dial like the hands of a clock, and the angle of the pointer's displacement from the vertical position is a measure of the angle of phase difference between the two sources of electromotive force to which the device is attached. Hence if the machine to be brought into synchronism rotates too fast, the pointer will move in one direction, and if it runs too slow, the pointer will move in the other direction. When coincidence in phase takes place, the pointer remains in a vertical stationary position. An instrument of this kind mounted on a swinging bracket is illustrated in Fig. 26.

Ground Detectors and Fuse Blocks

A ground detector is a device by means of which any leg or part of the circuit may be tested for grounds. Two lamps in series, connected to the ground at the point of connection between the two lamps, and so arranged by means of a switch that a test may be made, constitutes the general character of the apparatus. Whichever lamp burns brightest indicates the position of the ground. If the lamp connected to the right hand leg burns brightest, the left leg is grounded, and *vice versa.*

Fuses for alternating current service are generally mounted on porcelain backings, which in turn are contained in an iron box. They serve the purpose of opening the circuit when too heavy a current tends to flow through it. They consist of some easily fused metal which melts when a strong current flows through it, and thus disconnect the circuit. It is said that the fuse "blows" when the metal thus melts. When blowing, the operator is protected from injury by the position the fuses occupy in the porcelain foundation. A type of porcelain tube is employed which forms part of the porcelain foundation and which occupies a front position in the forward part of the fuse block; this contains the fuse and protects the lineman whether the box is near his hands or not, or whether it is opened or closed. In some designs of fuse blocks the porcelain tubes are readily removable. As they contain the fuse itself, it is evident that the removal of this tube and the insertion of another involves no risk of dangerous contact. The fuse, when blowing, expels the volatilized metal through the porcelain ends and thus protects the device from injury. It is to be understood that a fuse box must be waterproof. The presence of moisture would rapidly invite electrolytic and other actions. Heavy grounds, ultimately resulting in short circuits, would also be incurred.

Circuit Breakers

Circuit breakers are mechanical devices used instead of fuses to open an electric circuit when the current exceeds a certain predetermined value. They are the safety valve of the electric circuit, and prevent an excess of current to enter into a circuit where it would act destructively to the machinery and apparatus. The usual form of the circuit breaker is that of a switch normally held in its shut-down position by a latch and provided with a strong spring which acts in a direction tending to open the switch. A magnet is provided which is capable of releasing the latch and allowing the spring to throw the switch open as soon as the current reaches the danger point, or the value for which the magnet and latch are adjusted. The magnet is a solenoid, that it, it consists of a plunger around which are wound a few turns of heavy wire carrying a current. The current around the plunger magnetizes it, and causes it to move, thereby tripping the latch.

Circuit breakers are used instead of fuses because they are more sensitive; they can be adjusted to open exactly at a predetermined current value with the same precision as a safety valve opens at a given steam pressure. The most important advantage of the circuit breaker, however, is that it requires but a fraction of a second to throw in the circuit breaker switch, while it takes considerable time to replace a fuse. Besides the time gained, it is also much easier to operate in all respects. The only reason why circuit breakers are not used entirely in place of fuses is that their first cost is a great deal more than the cost of fuses. Small fuses are less objectionable than large ones, and for this reason circuit breakers are seldom used instead of small fuses.

The Compensator

The compensator, or as it is often called, the voltmeter compensator, is a device by means of which the voltmeter on the switchboard in the power station may be arranged to show the voltage between the transmission lines at some distant point, usually the point where the current is consumed. The transmission of power involves the sustaining of the correct voltage at the points, not only of distribution, but of consumption as well. The terminals of the feeding system must therefore be watched carefully to remedy any great difference in voltage between them and the station proper.

Losses in Power Transmission

If some estimate is made of the net results of power transmission from a standpoint of efficiency, based upon a general efficiency of 90 per cent per machine throughout the plant, the figures will show a lower efficiency than would be anticipated at first glance. Assuming the engine to deliver 1000 horsepower, the dynamo would yield 900 horsepower; the step-up transformers would give 10 per cent less, or 810 horsepower; the line would give 10 per cent less, or 729 horsepower; the step-down transformers would give 10 per cent less, or 656 horsepower; and the rotary converters and street lines 10 per cent less, or 590.4 horsepower. Higher percentages of efficiency than these are claimed for many plants, but a 30 per cent loss is not to be considered as very large from end to end of the complete power transmission system. Of course, the losses are not uniform as in the example above. In some of the apparatus the losses are more than 10 per cent and in some less. But the example above was chosen simply to show the method of obtaining the total efficiency when the losses in each part of the transmission system are known.

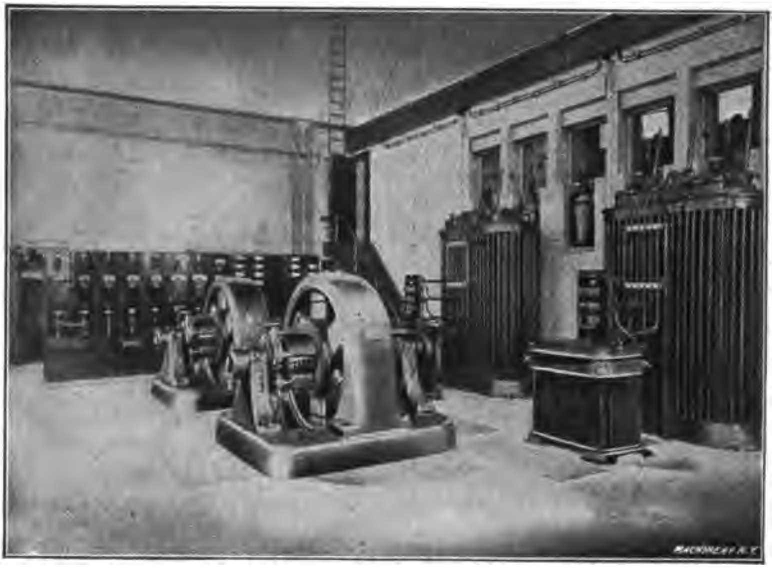


Fig. 27. The Interior of a Sub-station

In Fig. 27 is shown the interior of a sub-station. As will be seen in the illustration, there are two transformers placed against the wall and two rotary converters in the center of the room. In the back will be seen the switch-boards with their meters, switches and other apparatus.

CHAPTER III

POWER TRANSMISSION LINES

In the usual type of power transmission plant the power is generated at 2000 or 3000 volts, and is then transformed up by static transformers at the station end of the power line to 10,000 or 15,000 volts. A current of this voltage is then transmitted through the line to the receiving end, where a sub-station is located; the current is then stepped-down to a voltage suitable for the use to which it is to be put. Power transmission lines, hence, carry a very high voltage, and this, in fact, is one of the necessary requirements, both in order to reduce the heat losses and the size of the conductors required.

The material used in the wires is almost always copper, although aluminum is used to some extent. Both of these metals are used in their commercially pure state, and are selected on account of their high factor of conductivity. Aluminum is not as good a conductor as copper and a larger diameter of wire, therefore, is required to carry the same current, but even with this larger diameter the line is lighter than one of copper, on account of the low specific gravity of aluminum, and it is for this reason often used for long distance transmission lines. With the present low price of aluminum, the total cost of the line is not much different from that of a copper line. Aluminum is not used when it is necessary to insulate the wires, because, being larger in diameter, a greater amount of insulation material would become necessary, and this would increase the cost of the line considerably above one consisting of a copper conductor.

The area of copper wires is usually given in circular mils. By a circular mil is meant the area of a circle 0.001 inch in diameter. Table IV gives the area in circular mils of copper wire of various sizes according to the Brown & Sharpe wire gage. This table also gives the diameter and the resistance in ohms per foot. The resistance of an electrical conductor is expressed by the formula:

$$R = L \times f$$

in which R = total resistance in ohms,

L = length of the conductor in feet,

f = resistance of wire of given size in ohms per foot, as found from Table IV.

Square mils are sometimes used for expressing areas. A square mil is the area of a square whose side measures 0.001 inch. One square mil equals 1.27 circular mil. The diameters of copper wire used as conductors are given in the American or Brown & Sharpe wire gage. Wires of a size larger than No. 0000 are designated by their diameters in inches.

Effect of Resistance

The effect of the resistance in conductors shows itself in a drop in voltage, this drop being determined by Ohms' law. (See MACHINERY'S Reference Series No. 73, Principles and Applications of Electricity, Part I). There is also a loss of energy proportional to the C^2R loss referred to in the previous chapter. In addition there is a heating of the conductors, due to this energy loss, which is converted into heat. When the conductors increase in temperature the resistance increases, until all the energy generated is lost in heat. For this reason a conductor is capable of carrying only a certain amount of current with a given temperature rise. As a general rule, the current density should not exceed 1000 amperes per square inch of cross-section for copper conductors, but this value is too low for wire of small gage, and is too high for wire of large diameter. As an average, however, it may be used for general estimates.

TABLE IV. DIMENSIONS AND RESISTANCE OF COPPER WIRE

Dimensions			Resistance	
American or Brown & Sharpe Gage	Diameter in Inches	Area in Circular Mils	Ohms per Foot	
			At 68° F.	At 122° F.
0000	0.4600	211,600	0.0000489	0.0000547
000	0.4096	167,800	0.0000617	0.0000689
00	0.8648	183,100	0.0000778	0.0000869
0	0.3249	105,500	0.0000981	0.0001096
1	0.2898	88,690	0.0001287	0.0001382
2	0.2576	66,370	0.0001560	0.0001743
8	0.2294	52,630	0.0001967	0.0002198
4	0.2043	41,740	0.0002480	0.0002771
5	0.1819	88,100	0.0008128	0.0008495
6	0.1620	26,250	0.0008944	0.0004406
7	0.1448	20,820	0.0004973	0.0005556
8	0.1285	16,510	0.0006271	0.0007007
9	0.1144	18,090	0.0007908	0.0008885
10	0.1019	10,880	0.0009972	0.0011140
11	0.0907	8,234	0.0012570	0.0014050
12	0.0808	6,580	0.0015860	0.0017710
18	0.0720	5,178	0.0019990	0.0022840
14	0.0641	4,107	0.0025210	0.0028170
15	0.0571	8,257	0.0081790	0.0085520
16	0.0508	2,583	0.0040090	0.0044790
17	0.0453	2,048	0.0050550	0.0056480
18	0.0408	1,624	0.0068740	0.0071220

Insulation or covering is required for all conductors carrying electrical energy, excepting for wires used on pole lines. Even these wires are, however, often insulated. The insulation may serve the purpose of merely preventing the wires from coming into contact with each other, in which case a simple cotton or silk covering is used. When a high voltage is carried, the insulation serves the purpose of presenting a high specific resistance.

In speaking of the capacity of a conductor we have meant, so far, its capacity for carrying or transmitting current. The expression "electrostatic capacity" of a conductor, however, is the quantity of electricity that is required for charging the conductor to a given potential, or in other words, it is the quantity of electricity which must be imparted to the conductor as a charge in order to raise its potential a certain amount. The amount of electricity used for this purpose involves, of course, a loss of a part of the total amount of energy sent into the line. When the line is long the capacity may be appreciable. Formulas and tables will be given in the following for its calculation in all cases.

Capacity and Inductance in Power Lines

A power transmission line is affected in two respects, first by the effect of one wire upon the other, and of each of the wires upon the earth, and second by the effect of self and mutual inductance. These two effects are called the inductance and the capacity of the line, respectively, and constitute the losses met with in a power transmission. The capacity, in this case, is what is called the electrostatic or static capacity of the line, as has just been explained above. The capacity may be reduced by increasing the distance between the conductors, or in lead-covered cables, by using an insulating material having a low specific inductive capacity such as paper.

By mutual inductance is meant the inductive effect of one circuit on a separate circuit, the other circuit being in parallel in a power transmission. If, for example, an alternating current flows in one circuit, it sets up an electromotive force in a parallel circuit. This electromotive force is opposite in direction to the electromotive force impressed on the first circuit. The effects of mutual inductance may be reduced by increasing the distance between the circuits, the distance between the wires of the same circuit remaining the same. It is evident that this method is impractical beyond certain limits, when the wires of the two circuits are supported by the same poles. In this case a special arrangement as explained later must be used.

The conditions which make a circuit inductive or non-inductive may be regarded as those which individually or collectively add more or less of a varying magnetic field to the circuit. For instance, a core of iron around which a coil of wire carrying an alternating current is wound is an extreme case of inductance. The removal of the iron core reduces the degree of inductance, and the straightening of the wire from its coiled form still further reduces it. When two straight wires are employed for the purpose of transmitting electrical energy in the form of an alternating current, they have the least effect inductively upon each other when closest together. In other words, if one wire leading out, and the other leading back to the power house, are installed a short distance away from each other, the effects of self-induction are less than when they are widely separated, but a wide separation between high tension wires is relatively necessary as insulation could not otherwise be secured, particularly during conditions of great dampness or severe rain.

The distance between copper conductors will influence the degree of inductance to an extent indicated by the following figures: For a No. 0 Brown. & Sharpe gage pair of wires, run parallel and at the distances of 12, 18, 24 and 48 inches apart, the inductances in each case will be respectively 0.00254, 0.00276, 0.00293 and 0.00331 henry. A line necessarily has a certain amount of induction, which, when its true carrying capacity is estimated, calls for consideration. It is quite evident that the increasing value of high potentials necessitates the use of greater distances between the power lines than would be otherwise necessary. Tests have been made for the purpose of determining the pressure and distance over which spontaneous sparking would result. The results have been tabulated in a case where a wave form of current was employed with the spark leaping between needle points. A chart with a curve showing the relationship between the distance and voltage, with corresponding data, is given in Fig. 28. The diagrammatic form in which these facts are given will give some idea of the conditions resulting from the use of high pressures when the questions of inductance and insulation arise.

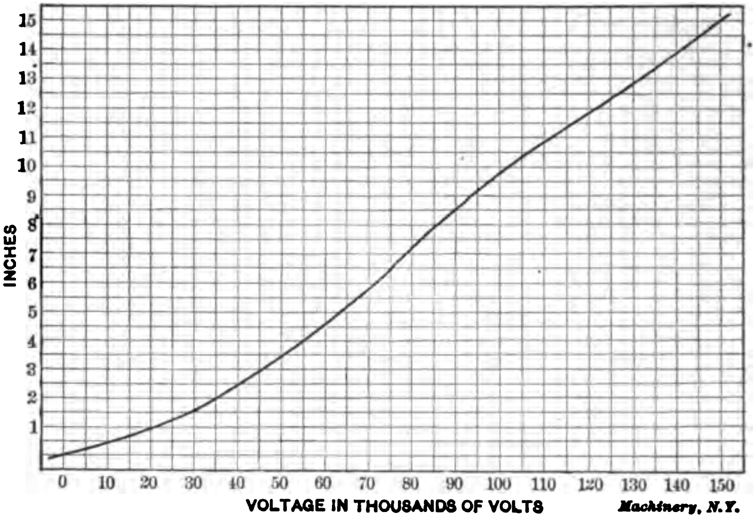


Fig. 28. Chart showing Relation between Voltage and Distance between Conductors

Calculating the Inductance Between Wires

Various tests may be made to ascertain the amount of inductance between two parallel wires of copper or aluminum by employing a galvanometer and measuring the results obtained. On the other hand, fairly accurate calculations can be made by selecting and using a reliable and simple formula for the same purpose.

Let A = distance between the wires in inches,
d = diameter of the wires in inches,
L = the inductance in henrys.

Then the total inductance per mile of circuit is found by the following formula:

$$L = 0.000558 \left[2.808 \log \left(\frac{2A}{d}\right) + 0.25\right]$$

A table can be made up, based upon this formula, in which the inductance is calculated for various distances between wires of different diameters.

The influence of inductance is overcome by the use of concentric conductors, or by conductors twisted around each other. The effects of inductance, unless remedied, are noticeable in the increased impedance in the line and the lag of the current.

The nearness of the conductors in pairs is detrimental in that it causes an increased mutual induction between them. To overcome this difficulty, where it is impractical to increase the distance between the wires, it is necessary to make use of the method of transposition in installing the wires. This consists of the crossing of the conductors at certain intervals so that a neighboring pair of wires remain inductively unaffected by the variations occurring in the first pair.

Capacity of Lines

The static capacity of transmission lines can be calculated by formulas covering insulated lead-covered cables, single conductors with a ground return, or two parallel conductors constituting the total circuit. The formula giving the capacity in microfarads per mile for lead-covered cables is:

$$C = \frac{38.83 \times K \times 10^{-8}}{\log \dfrac{D}{d}} \text{ per mile.}$$

For a single metallic circuit with ground return:

$$C = \frac{38.83 \times 10^{-8}}{\log \dfrac{4h}{d}} \text{ per mile.}$$

For metallic conductors running parallel to each other:

$$C = \frac{19.42 \times 10^{-8}}{\log \dfrac{2A}{d}} \text{ per mile.}$$

where C = capacity in microfarads,
K = specific inductive capacity of insulation = 1 for air, and 2.25 to 3.7 for rubber,
D = inner diameter of lead covering of cable,
d = diameter of conductor,
h = height of conductor above ground,
A = distance between wires.

The capacity of a circuit may be controlled as far as its effects are concerned by the introduction of a certain amount of inductance. By this means a neutralization of one by the other is effected successfully. The relationship of the two must be such that $C = 1 \div (2 \times \pi \times f)^2 \times L$, in which $f =$ the frequency, and $L =$ henrys.

Conductors Carrying Power

Conductors for carrying power can only be properly estimated on the basis of their weight, strength, temperature, resistance, capacity and inductance. The cost of the current carrying wire forms a considerable part of the expense of the erection of a complete power transmission line. The balance of the expense lies in the cost of the undertaking with regard to the poles, insulators, etc. The original law laid down by Lord Kelvin has undergone modification. His statement of the situation from an economic standpoint was as follows: "The interest on the cost of the copper of the line must be equal to the cost of the power wasted in the line." If the line cost $100,000, the interest at 6 per cent being $6,000 represented the dollars and cents value of the power that could be wasted in it without overstepping the economic law governing the best conditions of practice. The best conditions of practice, however, as outlined by the best engineering done in this field, show an expense in the insulation which far exceeded the anticipations of the theorists originally dealing with the subject. Copper and insulation are of greater importance as regards the integrity of the plant and its serviceability for continued power transmission than was formerly believed, because of the extraordinary high pressures employed to secure economical transmission.

The following formulas are recommended by one of the largest electrical manufacturing concerns in the United States. They relate entirely to the questions involved in power transmission, namely:

1. The area of the conductors in circular mils.
2. The weight of the copper of the conductors.
3. The voltage loss in the line.
4. The current in the main conductors.

The area of the power line in circular mils is obtained by employing this formula:

Area $= (D \times W \times C_1) \div (p \times E^2)$ in which

$W =$ power delivered in watts,
$D =$ distance of transmission in feet (one way),
$p =$ loss in line in per cent of power delivered,
$E =$ voltage between main conductors at receiving or consumer's end of the circuit.

The value of $C_1 = 2160$ for direct current, when $T = 1$, $B = 1$ and $A = 6.04$. The last symbols refer to characters used in formulas to follow. To obtain the value of the current in the main conductors, a formula of the following simple form is used:

$$\text{Current in main conductors} = W \times \frac{T}{E}.$$

When the power circuit carries a direct current $T = 1$. When the system is alternating, the value of T is obtained from the table below, in which it is given for single, two and three-phase currents:

System of Transmission	Power Factor in Per Cent				
	100	95	90	85	80
Single-phase system, value of $T=$	1.00	1.05	1.11	1.17	1.25
Two-phase system, (four wire), $T=$	0.50	0.53	0.55	0.59	0.62
Three-phase system (three wire), $T=$	0.58	0.61	0.64	0.68	0.72

Thus, $T=1$ for direct current; for single-phase with a power factor of 100 it also equals 1; for two-phase it equals 0.50; and for three-phase 0.58. But ideal conditions like these do not exist in power lines except under extraordinary circumstances. When the power factor is 80, the value of T becomes respectively 1.25, 0.62 and 0.72 with single, two and three-phase currents.

An illustration of this principle of application can be readily made by a case in which it is desirable to know the current in the main conductors with a given amount of power, say 100,000 watts, which is transmitted at a pressure of 10,000 volts by continuous current and single, two and three-phase currents, the power factor for all being 90.

With direct current. Current in main conductors $= 100{,}000 \times \dfrac{1}{10{,}000} = 10$ amperes.

With single-phase current. Current in main conductors $= 100{,}000 \times \dfrac{1.11}{10{,}000} = 11.1$ amperes.

With two-phase current. Current in main conductors $= 100{,}000 \times \dfrac{0.55}{10{,}000} = 5.5$ amperes.

With three-phase current. Current in main conductors $= 100{,}000 \times \dfrac{0.64}{10{,}000} = 6.4$ amperes.

The relative values in this case, when compared, show differences representing the amount of copper necessary for 10 amperes with direct current, 11.1 amperes with single-phase, 5.5 amperes with two-phase and 6.4 amperes with three-phase. The increase in the copper required with single-phase transmission over that required for a direct current, for equal quantities of power, is the difference between 11.1 amperes and 10 amperes. The weight of additional copper over a long line would readily prove the disadvantage of this if it were not outweighed by other considerations, such as comparatively easy handling as regards insulation. A direct high-tension current is not practical for power transmission because of the difficulty in attempting to secure insulation and commutation in direct-current motors under these conditions.

The weight of copper is calculated by the formula:

Pounds of copper $= (D^2 \times W \times C_1 \times A) \div (p \times E^2 \times 1{,}000{,}000)$.

The value of C_1 depends upon the system as does also A. Both are given in the following table, which covers the situation with regard to single, two and three-phase systems:

Systems	Values of A	Power Factor in Per Cent				
		Values of C_1				
		100	95	90	85	80
Single-phase	6.04	2160	2400	2660	3000	3380
Two-phase (four-wire)	12.08	1080	1200	1330	1500	1690
Three-phase (three-wire)	9.06	1080	1200	1330	1500	1690

In the case just cited, where $D = 100{,}000$ feet, $W = 100{,}000$ watts, $C_1 = 2660$, $A = 6.04$, $p = 10$, $E = 10{,}000$ volts, if the weight of copper for the single-phase system is calculated for a distance of 100,000 feet the result would be as follows, with a 90 per cent power factor and a 10 per cent loss.

Pounds of copper for single-phase system $= (100{,}000 \times 100{,}000 \times 100{,}000 \times 2660 \times 6.04) \div (10 \times 10{,}000 \times 10{,}000 \times 1{,}000{,}000) =$

$$\frac{100{,}000^3 \times 2660 \times 6.04}{10 \times 10{,}000^2 \times 10^6} = \frac{10^{15} \times 2660 \times 6.04}{10^{15}} \doteq 16{,}066 \text{ pounds.}$$

If the weight of copper is to be found for a two and a three-phase circuit under the same general conditions, an examination of the table will readily show that A for a two-phase system is 12.08, and C_1 for the same phase with a power factor of 90, has the value 1330. A further examination will show for three-phase, the value for A of 9.06, and for C_1 with a 90 per cent power factor 1330. Arranging the items as before, we have the following data for calculating the weight in pounds of copper of a two-phase system: $D = 100{,}000$ feet, $W = 100{,}000$ watts, $C_1 = 1330$, $A = 12.08$, $p = 10$, $E = 10{,}000$ volts.

Pounds of copper for a two-phase system $= (100{,}000^2 \times 100{,}000 \times 1330 \times 12.08) \div (10 \times 10{,}000^2 \times 10^6) = \dfrac{10^{15} \times 1330 \times 12.08}{10^{15}} =$ 16,066 pounds.

These calculations show no difference in the weight of wire.

The data supplied in connection with a three-phase system with a power factor of 90 are as follows: $D = 100{,}000$ feet, $W = 100{,}000$ watts, $C_1 = 1330$, $A = 9.06$, $p = 10$, $E = 10{,}000$ valts.

Pounds of copper for a three-phase system $= (100{,}000^2 \times 100{,}000 \times 1330 \times 9.06) \div (10 \times 10{,}000^2 \times 10^6) = \dfrac{10^{15} \times 1330 \times 9.06}{10^{15}} =$ 12,050 pounds.

The variation in weight due to the introduction of a three-phase system suggests the economic reason for its success over other methods. The results show equivalence in weight for a single and two-phase system as stated. The three-phase gives a favorable difference in weight of 25 per cent.

Where three-phase power transmission is a problem of many miles instead of the limited distance of the last examples, a formula is suggested for the weight of copper as follows:

Pounds of copper $= (M^2 \times \text{K. W.} \times 300{,}000{,}000) \div (p \times E^2)$,
where M = the distance of transmission in miles,
K. W. = the total energy delivered in kilowatts.

The power factor is assumed to be approximately 95 per cent.

If, for the purpose of illustrating the application of the formula, the following data are assumed:

$M = 100$ miles,
K. W. = 10,000,
$p = 10$,
$E = 100{,}000$ volts,

then the weight of copper will equal $\dfrac{100^2 \times 10{,}000 \times 300{,}000{,}000}{10 \times 100{,}000^2} = \dfrac{3 \times 10^{16}}{10^{11}} =$ 300,000 pounds of copper.

The Voltage Drop in the Line

The voltage drop in the line must receive consideration as the factor influencing the commercial aspect of the problem of power transmission more than any other. It is, in fact, the question of wasted energy in the line, which governs its cross-section for a given length. The weight is, therefore, an element governed by distance only in so far as the energy dissipated is duly considered. The greater the drop, the less the weight of copper for a given distance, other things being equal, and the less the drop, the greater the weight of copper required for a given distance under the same circumstances. The formula for the voltage lost in the power line is as follows:

Volts lost in line $= p \times E \times B \div 100$, where, as already stated,
p = per cent loss of power,
E = total pressure of line at the receiving end,
$B = 1$ for direct current.

The values of B for alternating current service, depend upon the size of the wire, frequency of the current and the power factor employed. In Table V values are given for wires 18 inches apart. If the difference in phase between the transmitting and receiving end is not very marked, these figures are reliable. Where the line loss exceeds 20 per cent and large conductors at 125 cycles are employed

TABLE V. VALUES OF FACTOR B

Size of Wire B. & S. Gage	25 Cycles				40 Cycles				60 Cycles				125 Cycles			
	Power Factor				Power Factor				Power Factor				Power Factor			
	95	90	85	80	95	90	85	80	95	90	85	80	95	90	85	80
0000	1.23	1.29	1.33	1.34	1.52	1.53	1.61	1.67	1.62	1.84	1.99	2.09	2.35	2.86	3.24	3.49
000	1.18	1.22	1.24	1.24	1.40	1.41	1.48	1.51	1.49	1.66	1.77	1.95	2.08	2.48	2.77	2.94
00	1.14	1.16	1.16	1.16	1.25	1.32	1.35	1.37	1.34	1.52	1.60	1.66	1.86	2.18	2.40	2.57
0	1.10	1.11	1.10	1.09	1.19	1.24	1.26	1.26	1.31	1.40	1.46	1.49	1.71	1.96	2.13	2.25
1	1.07	1.07	1.05	1.03	1.14	1.17	1.18	1.17	1.24	1.30	1.34	1.36	1.56	1.75	1.88	1.97
2	1.05	1.04	1.02	1.00	1.11	1.12	1.12	1.10	1.18	1.23	1.25	1.26	1.45	1.60	1.70	1.77
3	1.03	1.02	1.00	1.00	1.07	1.08	1.07	1.05	1.14	1.17	1.18	1.17	1.35	1.46	1.53	1.57
4	1.02	1.00	1.00	1.00	1.05	1.06	1.03	1.00	1.11	1.12	1.11	1.10	1.27	1.35	1.40	1.43
5	1.00	1.00	1.00	1.00	1.03	1.01	1.00	1.00	1.08	1.08	1.06	1.04	1.21	1.27	1.30	1.31
6	1.00	1.00	1.00	1.00	1.02	1.00	1.00	1.00	1.05	1.04	1.02	1.00	1.16	1.20	1.21	1.21
7	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.03	1.02	1.00	1.00	1.12	1.14	1.14	1.13
8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.02	1.00	1.00	1.00	1.09	1.10	1.09	1.07
9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.06	1.06	1.04	1.02
10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.04	1.03	1.00	1.00

the figures will fail. For lower frequencies and less loss they average up correctly; at about 10 per cent loss the most reliable results may be obtained. With the wires nearer together, the loss becomes less, until, if side by side, only the resistance loss remains.

General allowance should be made of, say, a power factor of 95 per cent for incandescent lighting and synchronous motors; 85 per cent for induction motors and lighting done together; and for induction motors alone about 80 per cent. The value of p in the previous calculations is the percentage of delivered power lost, not the percentage of loss in the line of the power at the generator end. The potential E is the voltage at the receiving end of the power line.

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