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by FRANK D. GRAHAM, B.S., M.S., M.E., E.E.

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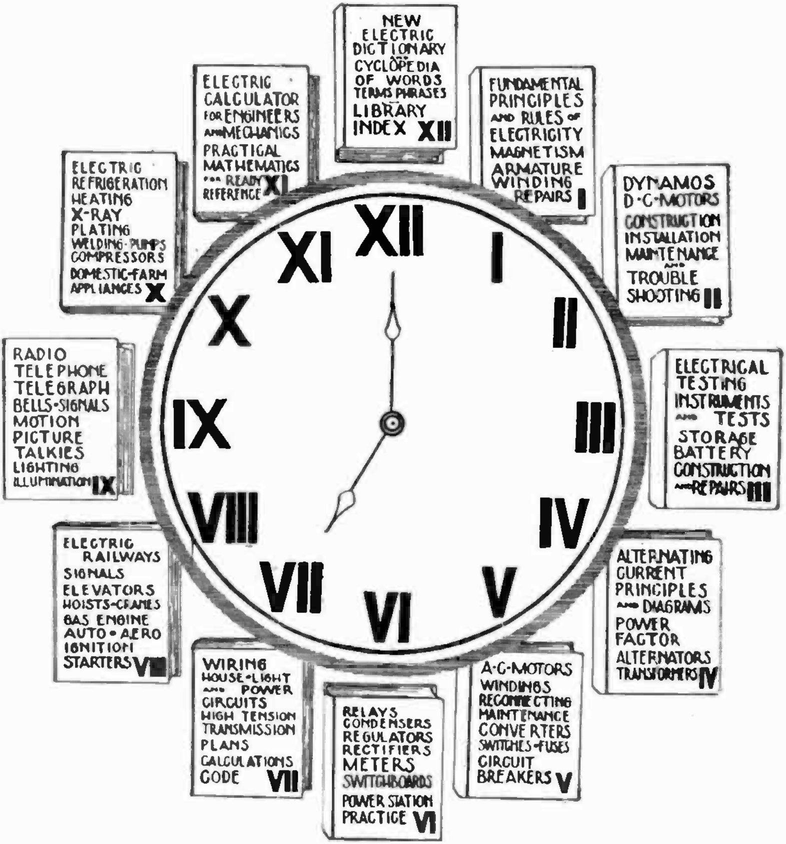

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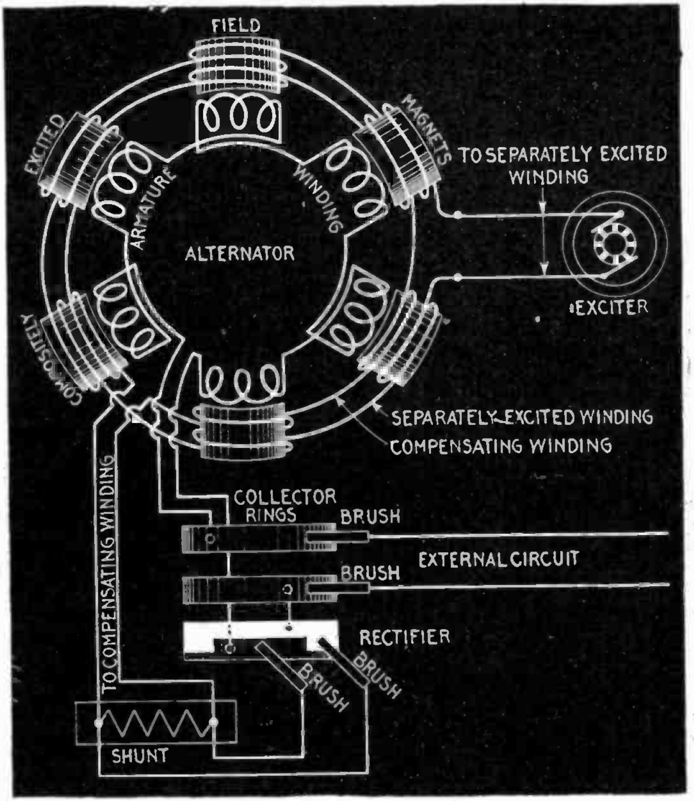

Wiring Scheme of Compositely Excited Alternator

Diagram of compositely excited alternator. The current for exciting the field magnets is obtained, partly from an exciter and partly from the windings of the alternator, being transformed into direct current by the *rectifier*. The connections are as shown. One end of the armature winding is connected to one of the collector rings; the other end, to the solid black part of the rectifier, as shown, the white part of the rectifier being connected to the other collector ring. Two brushes bear on adjacent teeth of the rectifier and are connected to the compensating winding circuit across which is a shunt. ***In operation,*** the separately excited coils set up the magnetism necessary for the generation of the voltage at no load. The main current coming from the armature is shunted, part going through the shunts and the remainder around the compensating winding, furnishing the additional magnetism necessary to supply the voltage to overcome the armature impedance. As shown, both field windings encircle every pole, but in some machines the rectified current will traverse a few poles only, the current from the exciter traversing the remainder.

Foreword

This series is dedicated to Electrical Progress—to all who have helped and those who may in the coming years help to bring further under human control and service to humanity this mighty force of the Creator.

The Electrical Age has opened new problems to all connected with modern industry, making a thorough working knowledge of the fundamental principles of applied electricity necessary.

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Finder

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To quickly and easily find information on any subject, read over the general chapter headings as shown in the large type—this brings the reader's attention to the general classification of information in this book.

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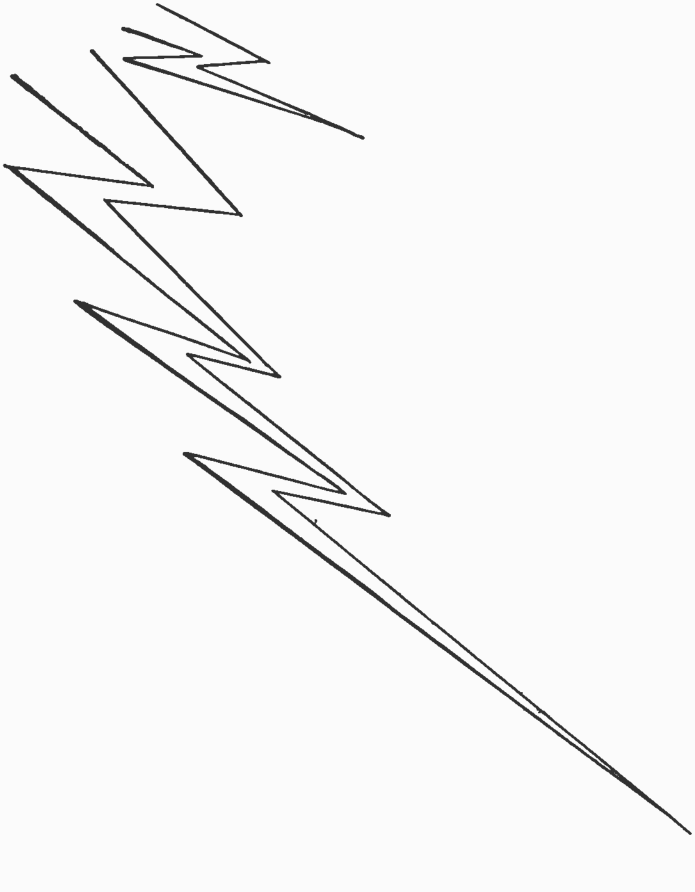
"An hour with a book would have brought to your mind,
The secret that took the whole year to find;
The facts that you learned at enormous expense,
Were all on a library shelf to commence."

FINDER

52 Transformers.......................1,627 to 1,710

53 Transformer Connections........1,711 to 1,742



CHAPTER 47

Alternating Currents

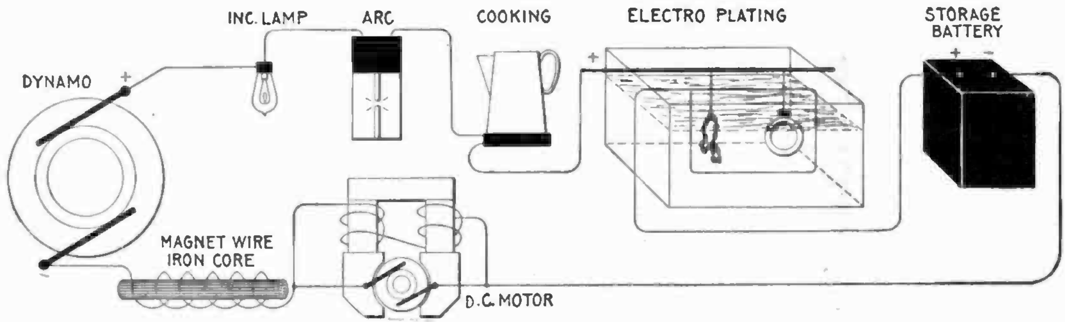
The word "Alternating" is used with a large number of electrical and magnetic quantities to denote that their magnitudes vary continuously, passing repeatedly through a definite cycle of values in a definite interval of time.

As applied to the flow of electricity, an alternating current may be defined as: *A current which reverses its direction in a periodic manner, rising from zero to maximum strength, returning to zero, and then going through similar variations in strength in the opposite direction;* these changes comprise the *cycle* which is repeated with great rapidity.

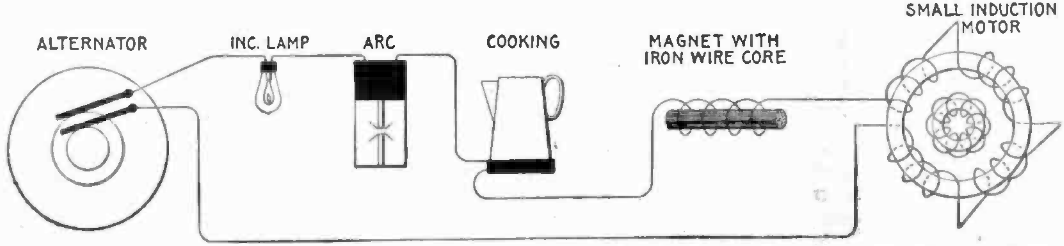
The properties of alternating currents are more complex than those of continuous currents, and their behavior more difficult to predict. This arises from the fact that the magnetic effects are of far more importance than those of steady currents. With the latter the magnetic effect is constant, and has no reactive influence on the current when the latter is once established. The lines of force, however, produced by alternating currents are changing as rapidly as the current itself, and they thus induce electric pressures in neighboring circuits, and even in adjacent parts of the same circuit. This inductive influence in alternating currents renders their action very different from that of continuous current.

Ques. What are the advantages of alternating current over direct current?

Ans. The reduced cost of transmission by use of high voltage transformers, greater simplicity of generators and



FIGS. 1,905 to 1,912.—Apparatus which operates successfully on a direct current circuit. The direct current will operate incandescent lamps, arc lamps, electric heating apparatus, electro-plating and typing bath, direct current motors; charge storage batteries, produce electro-chemical action. It will flow through a straight wire or just as freely through the same wire when wound over an iron bar.



FIGS. 1,913 to 1,918.—Apparatus which operates successfully on an alternating circuit. The alternating current will operate incandescent lamps, arc lamps, electric heating apparatus, alternating current motors. It will flow through a straight wire with slightly increased retarding effect, but if the wire be wound on an iron bar its strength is greatly reduced.

motors, facility of transforming from one voltage to another (either higher or lower) for different purposes.

The size of wire needed to transmit a given amount of electrical energy (watts) with a given percentage of drop, being *inversely proportional to the square of the voltage employed*, the great saving in copper by the use of alternating current at high pressure must be apparent. This advantage can be realized either by a saving in the weight of wire required, or by transmitting the current to a greater distance with the same weight of copper.

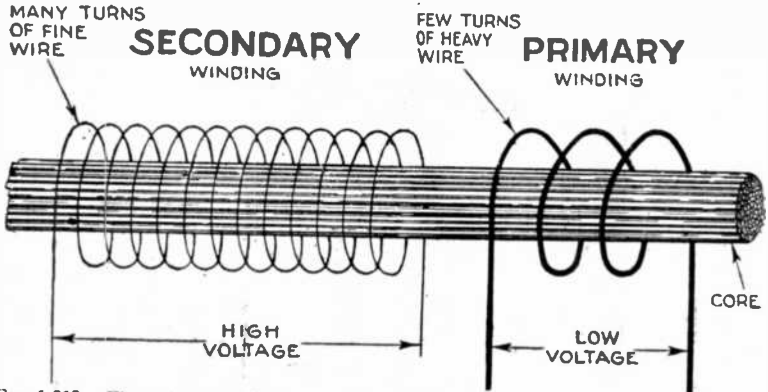


FIG. 1,919.—Elementary transformer consisting of: 1, core; 2, primary winding; 3, secondary winding.

In alternating current electric lighting, the primary voltage is usually at least 1,000 and often 2,000 to 10,000 volts.

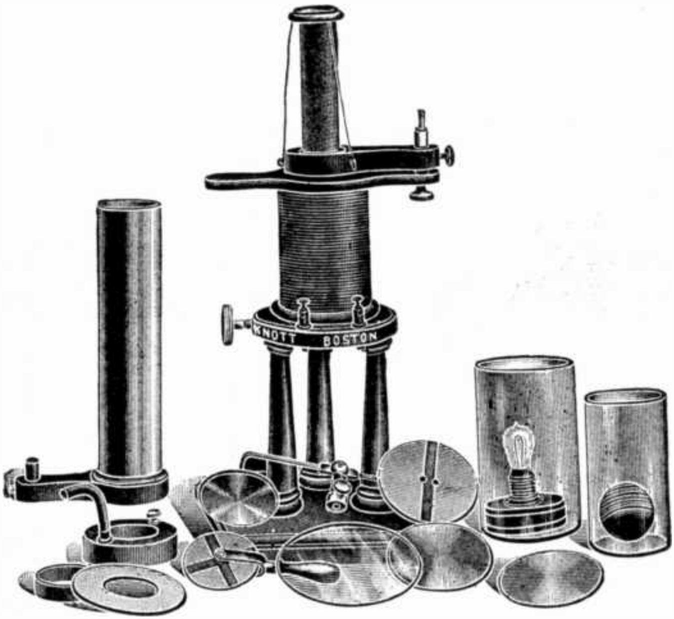
Ques. Why is alternating current used instead of direct current on constant pressure lighting circuits?

Ans. It is due to the greater ease with which the current can be transformed from higher to lower pressures.

Ques. How is this accomplished?

Ans. By means of simple transformers, consisting merely of two or more coils of wire wound upon an iron core.

Since there are no moving parts, the attention required and the likelihood of the apparatus getting out of order are small. The apparatus necessary for direct current consists of a motor dynamo set which is considerably more costly than a transformer and not so efficient.



FIGS. 1,920 to 1,932.—Knott electro-dynamic apparatus for alternating currents. This apparatus has been designed for the purpose of showing the repulsion and rotation effects produced by an alternating current. *It is designed* for a commercial circuit of 110 volts, the alternating current being recommended. A few of the experiments made with the apparatus are: 1, diaphragm made to vibrate in unison with the alternations of the current so as to give out a distinct tone; 2, repulsion of a copper disc held in proximity to the iron core on the balance arm; 3, the rotation of the copper disc caused by the revolving field; 4, the rotating ball. A copper ball, placed over the exposed end of the iron core and one half of the core covered with a copper disc, will rotate. By floating the ball in a jar of water, the rotation becomes rapid; 5, lighting of an electric lamp by means of the pulsations given out from the iron core, this being accomplished through the glass jar; 6, the suspension of a heavy metal ring placed around the iron core; 7, the comparative repulsion of copper and aluminum rings; 8, heating effect in a copper ring, shown by the boiling of a liquid.

Ques. What are some of the disadvantages of alternating current?

Ans. The high pressure at which it is used renders it dangerous, and requires more efficient insulation; alternating current

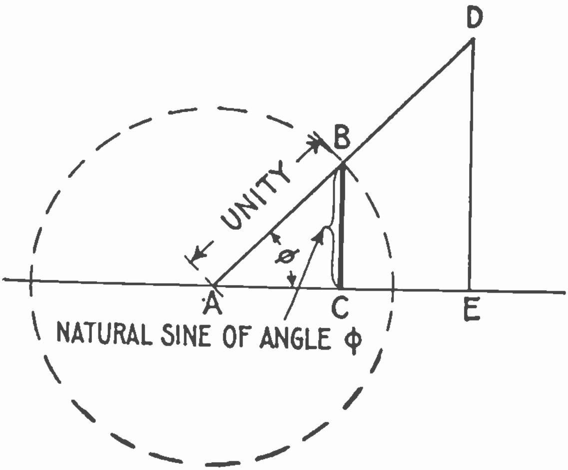


FIG. 1,933.—Diagram illustrating the sine of an angle. In order to understand the sine curve, it is necessary to know the meaning of the sine of an angle. This is defined as *the ratio of the perpendicular let fall from any point in one side of the angle to the other side divided by the hypothenuse of the triangle thus formed*. For instance, in the diagram, let AD and AE be the two sides of the angle ϕ, and DE, a perpendicular let fall from any point D, of the side AD, to the other side AE. Then, the sine of the angle (written $\sin\phi$) = DE ÷ AD. It is evident that if the perpendicular be let fall at a unit's distance from the apex A, as at B,

$$\sin\phi = \frac{BC}{AB} = \frac{BC}{1} = BC$$

This line BC, is called the *natural sine* of the angle, and its values for different angles are given in the table on page 921.

cannot be used for such purposes as electro-plating, charging storage batteries, etc.

Alternating Current Principles.—In the operation of a dynamo, as explained in Chapter 13, alternating currents are

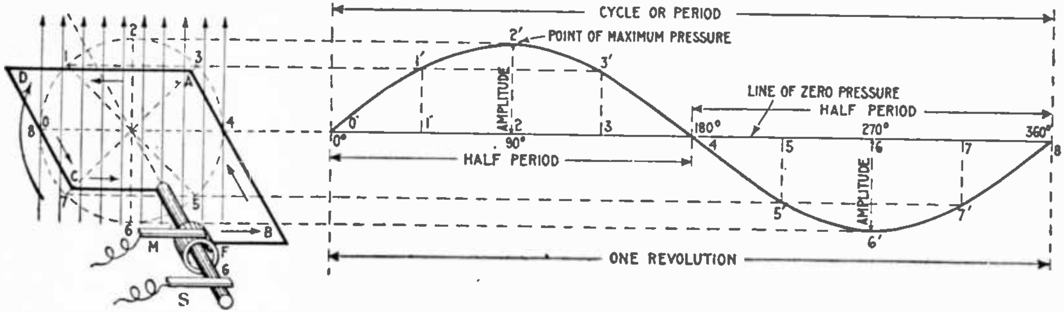


FIG. 1,934.—Construction and application of the sine curve. The sine curve is a wavelike curve used to represent the changes in strength and direction of an alternating current. At the left of the figure is shown an elementary alternator, consisting of a loop of wire ABCD, whose ends are attached to the ring F, and shaft G, being arranged to revolve in a uniform magnetic field, as indicated by the vertical arrows representing magnetic lines at equi-distances. The alternating current induced in the loop is carried to the external circuit through the brushes M and S. The loop, as shown, is in its horizontal position at right angles to the magnetic field. The dotted circle indicates the circular path described by AB, or CD, during the revolution of the loop. Now, as the loop rotates, the induced electric pressure will vary in such a manner that *its intensity at any point of the rotation is proportional to the sine of the angle corresponding to that point.* Hence, on the horizontal line which passes through the center of the dotted circle, take any length as 08, and divide into any number of equal parts representing fractions of a revolution, as 0°, 90°, 180°, etc. Erect perpendiculars at these points, and from the corresponding points on the dotted circle project lines (parallel to 08) to the perpendiculars; these intersections give points on the sine curve, for instance, through 2 at the 90° point of the revolution of the loop, and projecting over to the corresponding perpendicular gives 2′ 2, whose length is proportional to the electric pressure at that point. In like manner other points are obtained, and the curved line through them will represent the variation in the electric pressure for all points of the revolution. At 90° the pressure is at a maximum, hence by using a pressure scale such that the length of the perpendicular 2′2 for 90° will measure the maximum pressure, the length of the perpendicular at any other point will represent the actual pressure at that point. The curve lies above the horizontal axis during the first half of the revolution and below it during the second half, which indicates that the current flows in one direction for a half revolution, and in the opposite direction during the remainder of the revolution.

generated in the armature winding and are changed into direct current by the action of the commutator. It was therefore necessary in that chapter, in presenting the basic principles of the dynamo, to explain the generation of alternating currents at length, and the graphic method of representing the alternating current cycle by the sine curve. In order to avoid unnecessary repetition, the reader should carefully review the above mentioned chapter before continuing further. The diagram fig. 399, showing the construction and application of the sine

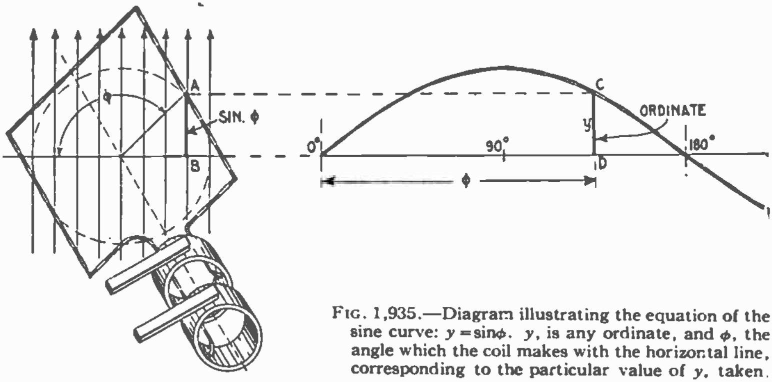


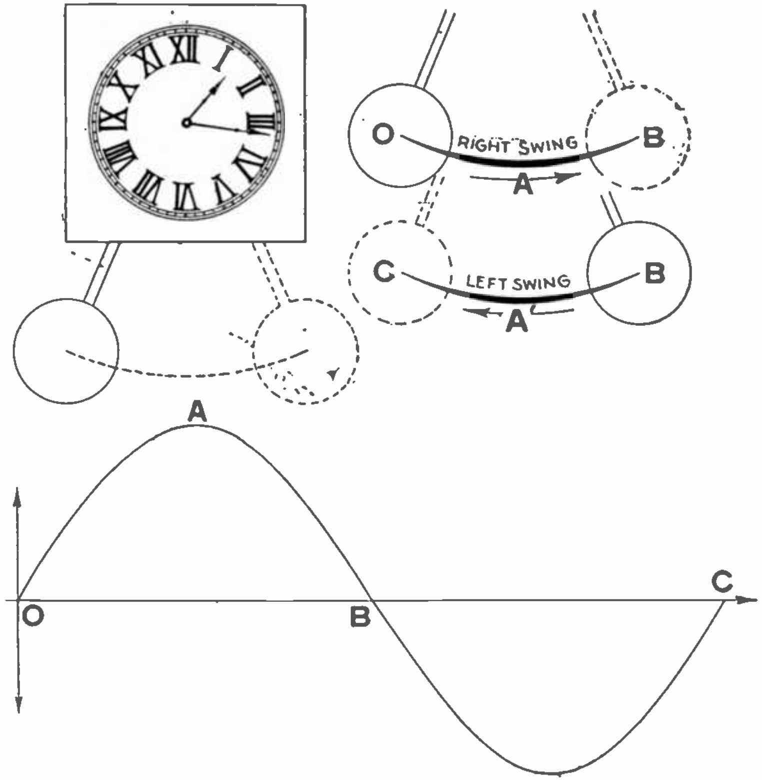
Fig. 1,935.—Diagram illustrating the equation of the sine curve: $y = \sin\phi$. y, is any ordinate, and ϕ, the angle which the coil makes with the horizontal line, corresponding to the particular value of y, taken.

curve to the alternating current, is, however, for convenience here shown enlarged in fig. 1,934.

In the diagram the various alternating current terms are graphically defined.

The alternating current, as has been explained, *rises from zero to a maximum, falls to zero, reverses its direction, attains a maximum in the new direction, and again returns to zero;* this comprises the *cycle.*

This series of changes can best be represented by a curve, whose abscissæ represent time, or degrees of armature rotation, and whose



FIGS. 1,936 to 1,939.—Clock pendulum analogy of alternating current. The pendulum swings first in one direction and then in the other, as indicated in figs. 1,937 and 1,938. At the end of each swing it slows down to a complete stop and then gradually speeds up in the opposite direction. As it passes through the lowest point it travels at maximum speed. Traveling toward the center its speed increases continually, and traveling away from the center its speed decreases continually. If a curve be constructed by plotting the speed with time and plotting the curve for a right swing above a reference line and the curve for a left swing below it, a diagram such as shown will be produced. The point O, indicates zero speed when the pendulum is at the extreme left and is just about to start on the right swing. The point A, represents the speed of the pendulum as it passes through the center. The point B, represents the end of the right swing with the pendulum stopped and ready to start the left swing and so on. Intermediate points represent the speed at corresponding times through the swing. Electricians use the same form of curve plotted with time to show the variations of current, current being substituted for speed.

ordinates, either current or pressure. The curve usually chosen for this purpose is the sine curve, as shown in fig. 1,934, because it closely agrees with that given by most alternators.

The equation of the sine curve is

$$y = \sin \phi$$

in which y, is any ordinate, and ϕ, the angle of the corresponding position of the coil in which the current is being generated as illustrated in fig. 1,935.

Ques. What is an alternation?

Ans. The changes which the current undergoes in rising from zero to maximum pressure and returning back to zero; that is, a single positive or negative "wave" or half period, as shown in fig. 1,940.

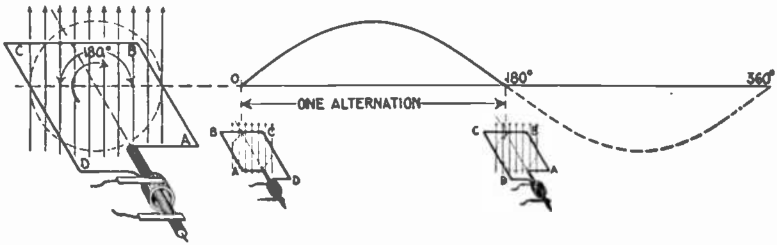


FIG. 1,940.—Diagram showing one *alternation* of the current in which the latter varies from zero to maximum and back to zero while the generating loop ABCD, makes one half revolution.

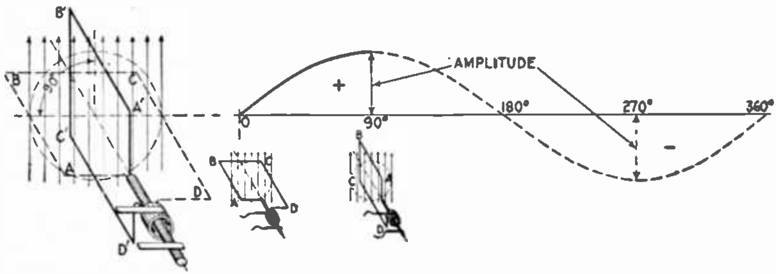


FIG. 1,941.—Diagram illustrating *amplitude* of the current. The current reaches its amplitude or maximum value in one quarter period from its point of zero value, as, for instance, while the generating loop moves from position ABCD, to A'B'C'D'. At three-quarter revolution, the current reaches its maximum value in the opposite direction.

Ques. What is the amplitude of the current?

Ans. The greatest value of the current strength attained during the cycle.

The foregoing definitions are also illustrated in fig. 1,934.

Ques. Define the term "period."

Ans. This is the time of one cycle of the alternating current.

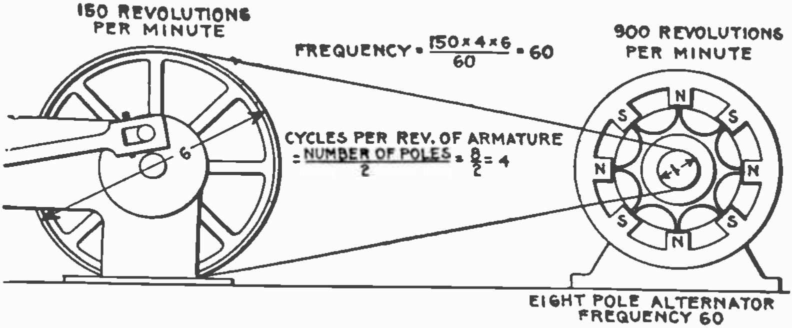


FIG. 1,942.—Diagram of alternator and engine, illustrating *frequency*. The frequency or *cycles per second* is equal to *the revolution of armature per second multiplied by one-half the number of poles per phase*. In the figure the armature makes 6 revolutions to one of the engine; one-half the number of poles = 8 ÷ 2 = 4, hence frequency = (150 × 4 × 6) ÷ 60 = 60. The expression in parentheses gives the cycles per minute, and dividing by 60, the cycles per *second*.

Ques. What is periodicity?

Ans. A term sometimes used for *frequency*.

Frequency.—If a slowly varying alternating current be passed through an incandescent lamp, the filament will be seen to vary in brightness, following the change of current strength. If, however, the alternations take place more rapidly than about 50 to 60 per second, the eye cannot follow the variations and the lamp appears to burn steadily. Hence it is important to consider the rate at which the alternations take place, or as it is called, the *frequency*, which is defined as: *the number of cycles per second.*

In a two pole machine, the frequency is the same as the number of revolutions *per second*, but in multipolar machines, it is greater in proportion to the number of *pairs* of poles per phase.

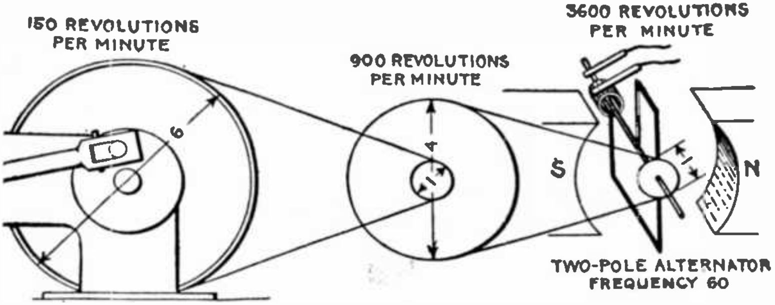


FIG. 1,943.—Diagram answering the question: Why are alternators always built multipolar? They are made multipolar because it is desirable that the frequency be high. It is evident from the figure that to obtain high frequency would require too many revolutions of the armature of a bipolar machine for mechanical safety—especially in large alternators. Moreover, a double reduction gear in most cases would be necessary, adding complication to the drive. Comparing the above illustration with fig. 1,942, shows plainly the reason for multipolar construction.

Thus, in an 8 pole machine, there will be four cycles per revolution. If the speed be 900 revolutions per minute, the frequency is

$$\frac{8}{2}\times\frac{900}{60}=60\sim$$

The symbol $\sim$ is read "cycles per second."

Ques. What frequencies are used in commercial machines?

Ans. The two standard frequencies are 25 and 60 cycles.

Ques. For what service are these frequencies adapted?

Ans. The 25 cycle frequency is used for conversion to direct current, for alternating current railways, and for machines of large size; the 60 cycle frequency is used for general distribution for lighting and power.

The frequency of 40 cycles, which once was introduced as a compromise

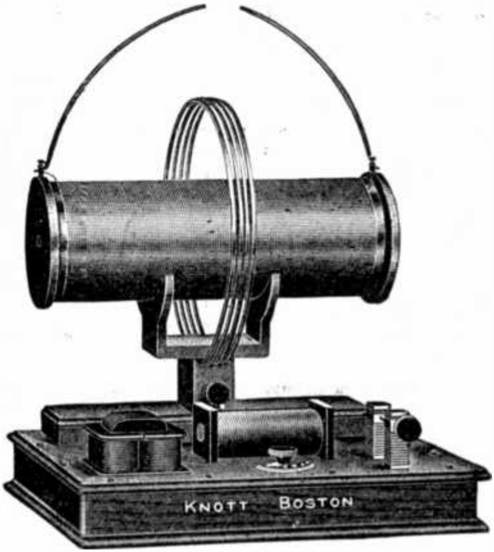


FIG. 1,944.—Knott frequency inductive apparatus. *It consists of* an open type of resonator with closed core type of transformer and silver spark gap. Designed for a comprehensive study of the high frequency field, including wireless telegraph waves and kindred subjects. Excites all types of vacuum tubes and will produce X-Rays. Connected on a 110-volt alternating current, will furnish a discharge of any desired value up to its full capacity—about 12 inches.

between 25 and 60 has been found not desirable, as it is somewhat low for general distribution, and higher than desirable for conversion to direct current.

Ques. What are the advantages of low frequency?

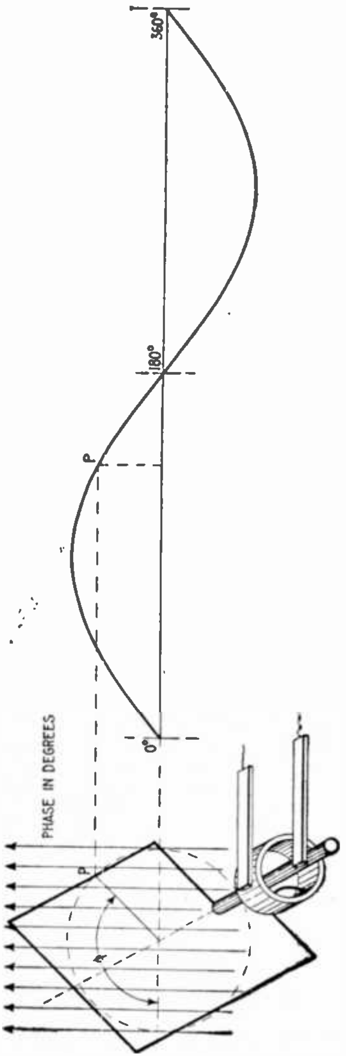


FIG. 1,945.—Diagram illustrating "phase." In wave, vibratory, and simple harmonic motion, phase may be defined as: *the portion of one complete vibration, measured in angle or in time, that any moving point has executed.*

Ans. The number of revolutions of the *rotor* is correspondingly low; arc lamps can be more readily operated; better pressure regulation; small motors such as fan motors can be operated more easily from the circuit.

Phase.—As applied to an alternating current, phase denotes *the angle turned through by the generating element reckoned from a given instant.** Phase is usually measured in degrees from the initial position of zero generation.

If in the diagram fig. 1,945, the elementary armature or loop be the generating element, and the curve at the right be the sine curve representing the current, then the phase of any point *p*, will be the angle ϕ or angle moved through from the horizontal line, the starting point.

Ques. What is phase difference?

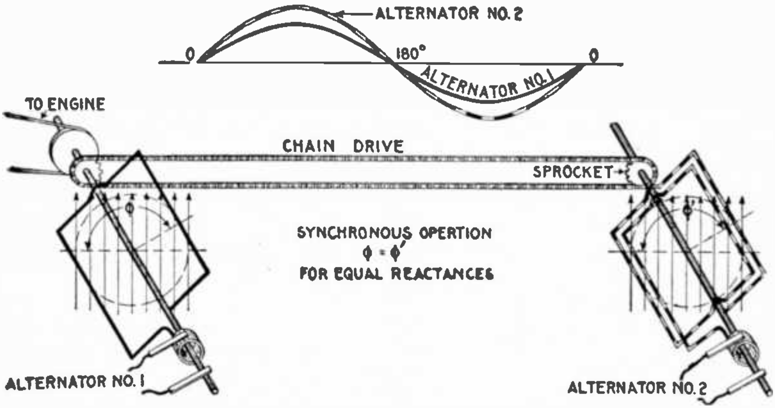
*NOTE.—*Phase.* Another definition: *Any position on an a.c. or pressure curve as indicated by some reference position.* Usually the phase position is defined by specifying the number of electrical degrees between the phase and the reference position.

Ans. The angle between the phases of two or more alternating current quantities as measured in degrees.

Ques. What is phase displacement?

Ans. A change of phase of an alternating pressure or current.

Synchronism.—This term may be defined as: *the simultaneous occurrence of any two events*. Thus two alternating currents or pressures are said to be "in synchronism" *when they have the same frequency and are in phase.*



FIGS. 1,946 and 1,947.—Diagram and sine curves illustrating *synchronism*. If two alternators, with coils in parallel planes, be made to rotate at the same speed by connecting them with chain drive or equivalent means, they will then be "in synchronism;" that is, the alternating pressure or current in one will vary in step with that in the other. In other words, the cycles of one take place with the same frequency and at the same time as the cycles of the other as indicated by the curves, fig. 1,946. It should be noted that the maximum values are not necessarily the same but the maximum and zero values must occur at the same time in both machines, and the maximum value must be of the same sign If the waves be distorted the maximum values may not occur simultaneously. See fig. 2,118, on page 1,508.

Ques. What does the expression "in phase" mean?

Ans. Two alternating quantities are said to be in phase, when there is no phase difference between; that is when the angle of phase difference equals zero.

Thus, the current is said to be in phase with the pressure when it neither lags nor leads, as in fig. 1,948.

A rotating cylinder, or the movement of an index or trailing arm is brought into synchronism with another rotating cylinder or another index or trailing arm, not only when the two are moving with exactly the same speed, but when in addition they *are simultaneously moving over similar portions of their respective paths.*

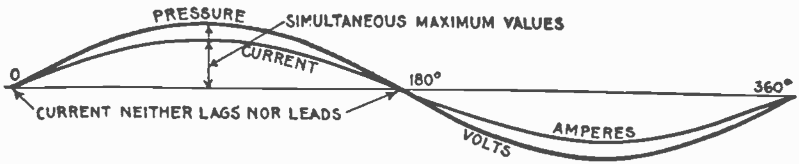


FIG. 1,948.—Pressure and current curves illustrating the term "in phase." The current is said to be *in phase* with the pressure when it *neither* lags nor leads.

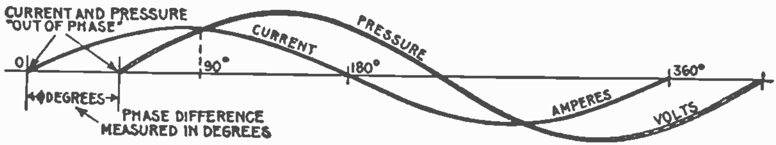


FIG. 1,949.—Pressure and current curves illustrating the term "out of phase." The current is said to be *out of phase* with the pressure when it *either* lags or leads, that is when the current is not in synchronism with the pressure. In practice the current and pressure are nearly always out of phase.

When there is phase difference, as between current and pressure, they are said to be "out of phase" the phase difference being measured as in fig. 1,949 by the angle ϕ.

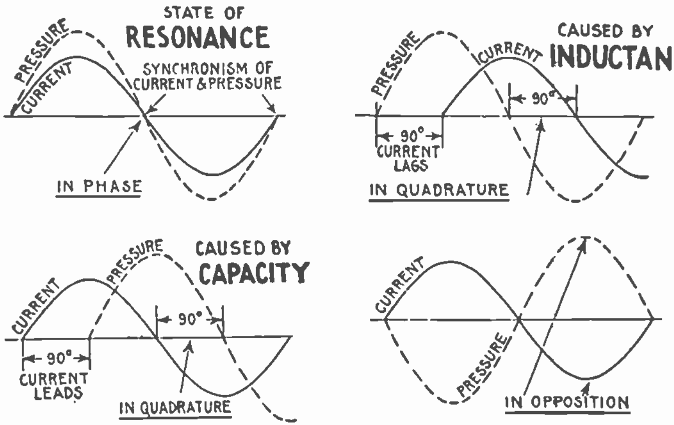
When the phase difference is 90° as in fig. 1,951 or 1,952, the two alternating quantities are said to be *in quadrature*; when it is 180°, as in fig. 1,953, they are said to be *in opposition.*

When they are in quadrature, one is at a maximum when the other is at zero; when they are in opposition, one reaches a positive maximum when the other reaches a negative maximum, being at each instant opposite in sign.

Ques. What is a departure from synchronism called?

Ans. Loss of synchronism.

Maximum Volts and Amperes.—In the operation of an alternator, the pressure and strength of the current are continually rising, falling and reversing.



FIGS. 1,950 to 1,953.—Phase relations of the current.

During each cycle there are two points at which the pressure or current reaches its greatest value, being known as the *maximum value*. This maximum value is not used to any great extent, but it shows the maximum to which the pressure rises, and hence, the greatest strain to which the insulation of the alternator is subjected.

Average Volts and Amperes.—Since the sine curve is used to represent the alternating current, the *average value* may be defined as: *the average of all the ordinates of the curve for one-half of a cycle.*

Ques. Of what use is the average value?

Ans. It is used in some calculations but, like the maximum value, not very often. The relation between the average and virtual value is of importance as it gives the form factor.

Virtual Volts and Amperes.—The virtual* value of an

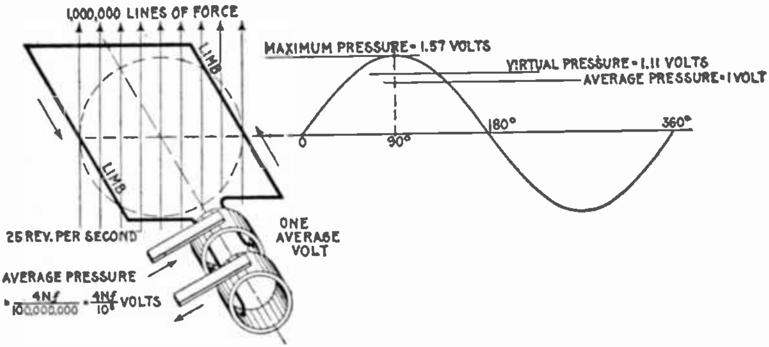


FIG. 1,954.—Elementary alternator developing one average volt. If the loop make one revolution per second, and the maximum number of lines of force embraced by the loop in the position shown (the zero position) be denoted by N, then each limb will cut 2N lines per second, because it cuts every line during the right sweep and again during the left sweep. Hence each limb develops an average pressure of 2N units (C.G.S. units), and as both limbs are connected in series, the total pressure is 4N units *per revolution*. Now, if the loop make f, revolutions *per second* instead of only one, then f, times as many lines will be cut *per second*, and the average pressure will be 4N f units. Since the C.G.S. unit of pressure is so extremely small, a much greater practical unit called the *volt* is used, which is equal to 100,000,000, or 10^8 C.G.S. units are employed. Hence average voltage $= 4Nf \div 10^8$. The value of N, in actual machines is very high, being several million lines of force. The illustration shows one set of conditions necessary to generate one average volt. The maximum pressure developed is $1 \div .637 = 1.57$ volts; virtual pressure $= 1.57 \times .707 = 1.11$ volts.

*NOTE.—"*I adhere* to the term *virtual*, as it was in use before the term *efficace* which was recommended in 1889 by the Paris Congress to denote the *square root of mean square* value. The corresponding English adjective is *efficacious*; but some engineers mistranslate it with the word *effective*. I adhere to the term *virtual* mainly because the adjective *effective* is required in its usual meaning in kinematics to represent the resolved part of a force which acts obliquely to the line of motion, the effective force being the whole force multiplied by the cosine of the angle at which it acts with respect to the direction of motion. Some authors use the expression 'R. M. S value' (meaning 'root mean square') to denote the virtual or quadratic mean value."—*S. P. Thompson.*

alternating pressure or current *is equivalent to that of a direct pressure or current which would produce the same effect;* those effects of the pressure and current are taken which are not affected by rapid changes in direction and strength—in the case of pressure, the reading of an electrostatic volt meter, and in the case of current, the heating effect.

The attraction (or repulsion) in electrostatic volt meters is proportional to the square of the volts.

The readings which these instruments give, if first calibrated by using

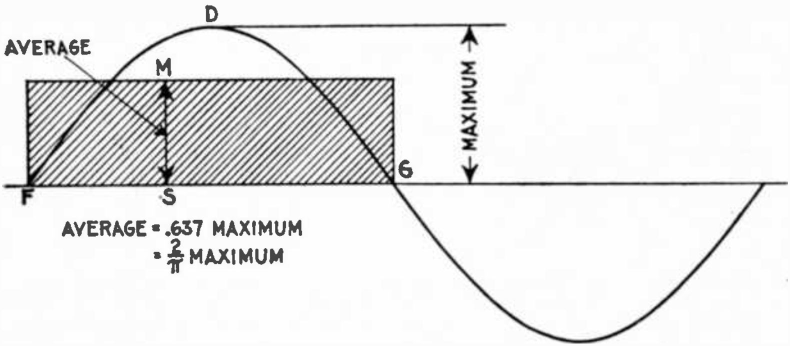


FIG. 1,955.—Maximum and average values of the sine curve. The average value of the sine curve is represented by an ordinate MS, of such length that when multiplied by the base line FG, will give a rectangle MFSG, whose area is equal to that included between the curve and base line FDGS.

steady currents, are not true means, but are *the square roots of the means of the squares.*

Now the mean of the squares of the sine (taken over either one quadrant or a whole circle) is ½; hence the *square root of mean square* value of the sine functions is obtained by multiplying their maximum value by $1 \div \sqrt{2}$, or by .707.

The arithmetical mean of the values of the sine, however, is .637. Hence an alternating current, if it obey the sine law, will produce a heating effect greater than that of a steady current of the same average strength, by the ratio of .707 to .637; that is, about 1.11 times greater.

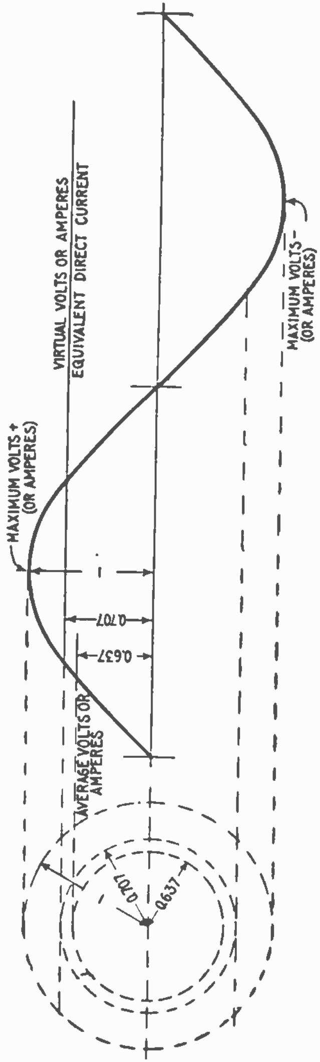


FIG. 1,956.—Diagram illustrating "virtual" volts and amperes. The word *virtual* is defined as: *Being in essence or effect, not in fact; not actual, but equivalent, so far as effect is concerned.* As applied to the alternating current; it denotes an imaginary direct current of such value as will produce an effect equivalent to that of the alternating current. Thus, a *virtual pressure* of 1,000 volts is one that would produce the same deflection in an electrostatic volt meter as a direct pressure of 1,000 volts; a *virtual current* of 10 amperes is that current which would produce the same heating effect as a direct current of 10 amperes.

If a Cardew volt meter* be placed on an alternating circuit in which the volts are oscillating between maxima of +100 and −100 volts, it will read 70.7 volts, though the arithmetical mean is really only 63.7; notwithstanding this, 70.7 steady volts would be required to produce an equal reading.

The matter may be looked at in a different way. If an alternating current is to produce in a given wire the same amount of effect as a continuous current of 100 amperes, since the alternating current goes down to zero twice in each period, it is clear that it must at some point in the period rise to a maximum greater than 100 amperes. How much greater must the maximum be? The answer is that, if it undulate up and down with a pure wave form, its maximum must be $\sqrt{2}$ times as great as the virtual mean; or conversely the virtual amperes will be equal to the maximum divided by $\sqrt{2}$. In fact, to produce equal effect, the equivalent direct current will be a kind of mean between the maximum and the zero value of the alternating current; but it must not be the arithmetical mean, nor the geometrical mean, nor the harmonic mean, but the *quadratic* mean; that is, it will be

*NOTE.—*Cardew volt meter.*—A variety of volt meter which indicates electric pressure *by the passage of the current through a slender wire which, due to the heating effect of the current, expands and moves the index needle upon the scale.*

the *square root of the mean of the squares* of all the instantaneous values between zero and maximum.

Effective Volts and Amperes.—Virtual pressure, although already explained, may be further defined as the pressure *impressed* on a circuit. Now, in nearly all circuits the impressed or virtual pressure meets with an opposing pressure due to inductance and hence the *effective* pressure is something less than the virtual, being defined as *that pressure which is*

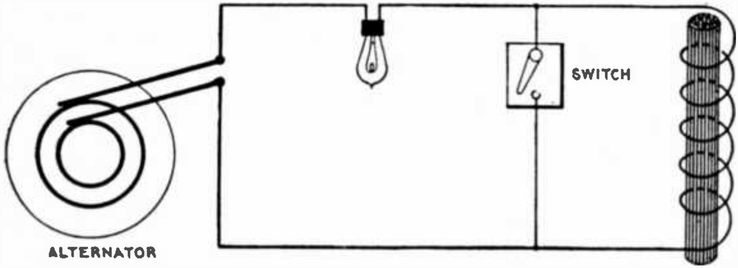


Fig. 1,957.—Diagram illustrating *virtual* and *effective* pressure. If the coil be short circuited by the switch and a constant virtual pressure be impressed on the circuit, the whole of the impressed pressure will be effective in causing current to flow around the circuit. In this case the virtual and effective pressures will be equal. If the coil be switched into circuit, the reverse pressure due to self induction will oppose the virtual pressure; hence, the effective pressure (which is the difference between the virtual and reverse pressures) will be reduced, the virtual or impressed pressure remaining constant all the time. A virtual current *is that indicated by an ammeter regardless of the phase relation between current and pressure.* An effective current *is that indicated by an ammeter when the current is in phase with the pressure. In practice,* the current is hardly ever in phase with the pressure, usually lagging, though sometimes leading in phase. Now the greater this phase difference, either way, the less is the power of a given virtual current to do work. With respect to this feature, effective current may be defined as: *that proportion of a given virtual current which can do useful work.* If there be no phase difference, then effective current is equal to virtual current.

available for driving electricity around the circuit, or for doing work. The difference between virtual and effective pressure is illustrated in fig. 1,957.

Ques. Does a given alternating voltage affect the insulation

of the circuit differently from a direct pressure of the same value?

Ans. It puts more strain on the insulation in the same proportion as the maximum pressure exceeds the virtual pressure.

Form Factor.—This term was introduced by Fleming, and denotes the ratio of the virtual value of an alternating wave to the average value. That is

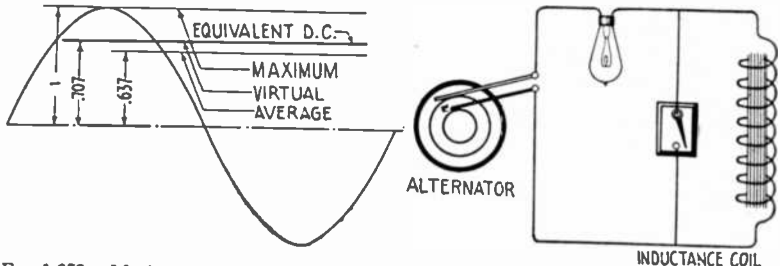


FIG. 1,958.—Maximum, *virtual* and average volts. *The virtual value of an alternating pressure or current is equivalent to that of a direct pressure or current which would produce the same effect.* If a Cardew volt meter be placed on an alternating current circuit in which the volts are oscillating between maxima of +100 and −100 volts, it will read 70.7 volts, though the arithmetical mean is really only 63.7; not withstanding this, 70.7 steady volts would be required to produce an equal reading. The word *effective is commonly*, yet *erroneously used for virtual.*

$$\text{form factor} = \frac{\text{virtual value}}{\text{average value}} = \frac{.707}{.637} = 1.11$$

Ques. What does this indicate?

NOTE.—*The form factor* of a wave shape is significant for certain purposes, as for example in the determination of hysteresis losses in a transformer, in which case the loss becomes greater as the form factor becomes less and vice versa under constant *r.m.s.* supply voltages of different wave shapes. *In general,* however, form factor has no useful significance as an indication of the shape of a wave or of its departure from a sine wave. An alternating wave may be composed of a fundamental sine wave and harmonics with frequencies that are multiples of the fundamental frequency, consequently the form factor of such a complex wave depends upon the amplitude and relative positions of these harmonics.—*Hausman.*

Ans. It gives the relative heating effects of alternating and direct currents, as illustrated in figs. 1,960 and 1,961.

That is, the alternating current will have about 11 per cent. more heating power than the direct current which is of the same *average* strength.

If an alternating current volt meter be placed upon a circuit in which the volts range from +100 to −100, it will read 70.7 volts, although the arithmetical average, irrespective of + or − sign, is only 63.7 volts. If the volt meter be connected to a direct current circuit, the pressure necessary to give the same reading would be 70.7 volts; this will give the same heating effect.

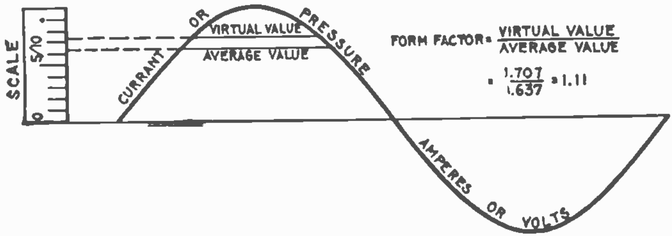


FIG. 1,939.—Current or pressure curve illustrating *form factor*. It is simply *the virtual value divided by the average value*. For a sine wave the virtual value is $\frac{1}{\sqrt{2}}$ times the maximum, and the average is $\frac{2}{\pi}$ times the maximum, so that the form factor is $\frac{\pi}{2\sqrt{2}}$ or 1.11. The induction wave which generates an alternating pressure wave has a maximum value proportional to the area, that is, to the average value of the pressure wave. Hence the induction values corresponding to two pressure waves whose virtual values are equal, will be inversely proportional to their form factors. This is illustrated by the fact that a *peaked* wave causes less hysteresis loss in a transformer core than a flat topped wave, owing to the higher form factor of the peaked wave. See wave forms, figs. 1,962 to 1,965.

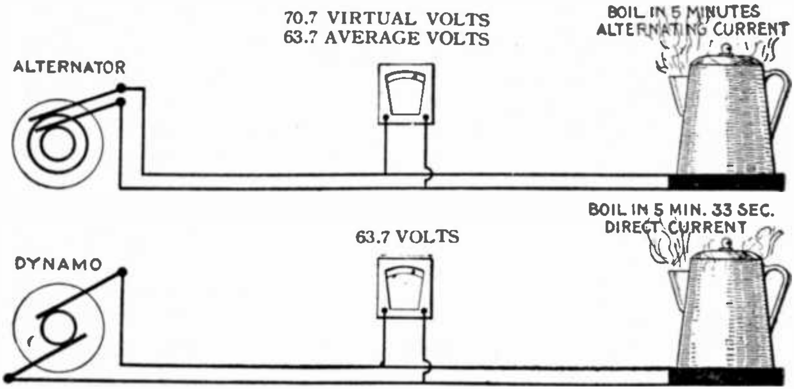
Ques. What is the relation between the shape of the wave curve and the form factor?

Ans. The more peaked the wave, the greater the value of its form factor.

A form factor of units would correspond to a rectangular wave; this is the least possible value of the form factor, and one which is not realized in commercial machines.

Wave Form.—There is always more or less irregularity in the shape of the current waves as met in practice, depending upon the construction of the alternator.

The ideal wave curve is the so-called *true sine wave*, and is obtained with a rate of cutting of lines of force, by the armature coils, equivalent to the swing of a pendulum, which increases in speed from the end to the middle of the swing, decreasing at

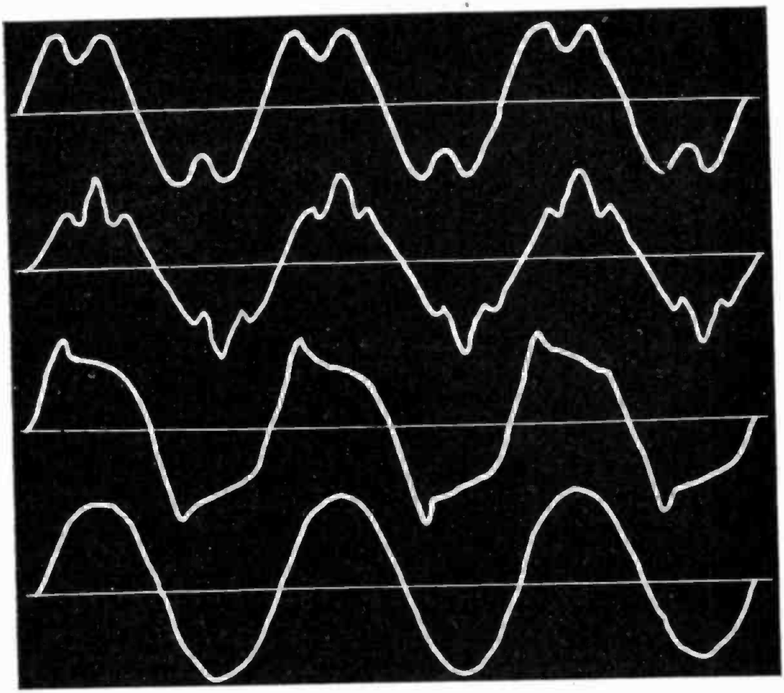


FIGS. 1,960 and 1,961.—Relative heating effects of alternating and direct currents. If it take, say five minutes to produce a certain heating effect with alternating current at say 63.7 *average* volts, it will take 33 seconds longer with direct current at the same pressure, that is, the alternating current has about 11 per cent. more heating power than the direct current of the same *average* pressure. The reader should be careful not to get a wrong conception of the above; it does not mean that there is a saving by using alternating current. When both volt meters read the same, that is, when the *virtual* pressure of the alternating current is the same as the direct current pressure, the heating effect is of course the same.

the same rate after passing the center. This swing is expressed in physics, as "simple harmonic motion."

The losses in all secondary apparatus are slightly lower with the so-called *peaked* form of wave. For the same virtual voltage, however, the top of the peak will be much higher, thereby submitting the insulation to that much greater strain.

By reason of the fact that the losses are less under such wave forms, many manufacturers in submitting performance data on transformers recite that the figures are for sine wave conditions, stating further that if the transformers are to be operated in a circuit more peaked than the sine wave, the losses will be less than shown.



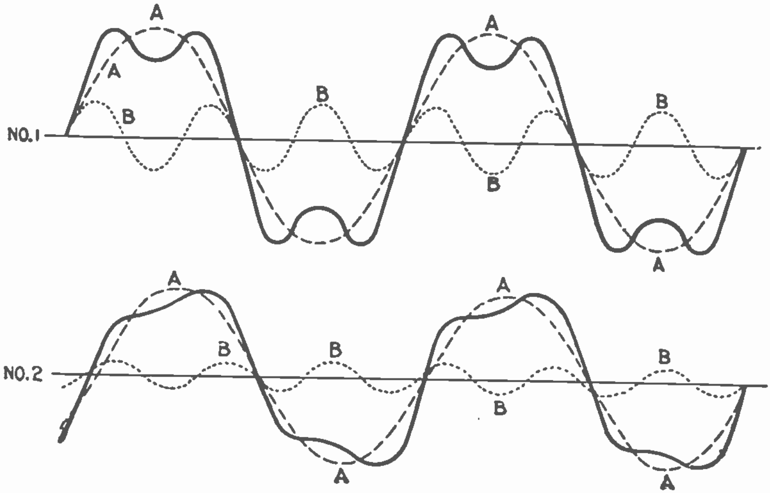
FIGS. 1,962 to 1,965.—Various forms of pressure or current waves. Figs. 1,962 to 1,964 show the general shape of the waves produced by some alternators used largely for lighting work and having toothed armatures. The effect of the slots and shape of pole pieces is here very marked. Fig. 1,965 shows a wave characteristic of large alternators designed for power. transmission and having multi-slot or distributed windings.

The slight saving in the losses of secondary apparatus, obtained with a peaked wave, by no means compensates for the increased insulation strains and an alternator having a true sine wave is preferred.

Ques. What determines the form of the wave?

Ans. 1. The number of coils per phase per pole, 2, shape of pole faces, 3, eddy currents in the pole pieces, and 4, the air gap.

Ques. What are the requirements for proper rate of cutting of the lines of force?



FIGS. 1,966 and 1,967.—Resolution of complex curves into sine curves. The heavy curve can be resolved into the simpler curves A and B, shown in No. 1, the component curves A and B, have in the ratio of three to one; that is, curve B, has three times as many periods per second as curve A. All the curves, however, cross the zero line at the same time, and the resultant curve, though curiously unlike either of them, has a certain symmetry. In No. 2 the component curves, besides having periods in the ratio of three to one, cross the zero line at different points. The resultant curve produced is still less similar to its components, and is curiously and unsymmetrically humped. At first sight it is difficult to believe that such a curious curve could be resolved into two such simple and symmetrical ones. In both figures the component curves are sine curves, and as the curves for sine and cosine functions are exactly similar in form, the simplest supposition that can be made for the variation of pressure or of current is that both follow a *sine law*.

Ans. It is necessary to have, as a minimum, two coils per phase per pole in three phase work.

Ques. What is the effect of only one coil per phase per pole?

Ans. The wave form will be distorted as shown in fig. 1,968.

Ques. What is the least number of coils per phase per pole that should be used for two and three phase alternators?

FIG. 1,968 —Reproduction of oscillograph record of wave form of alternator with one coil per phase per pole. Here the so-called "super-imposed harmonic" is clearly indicated.

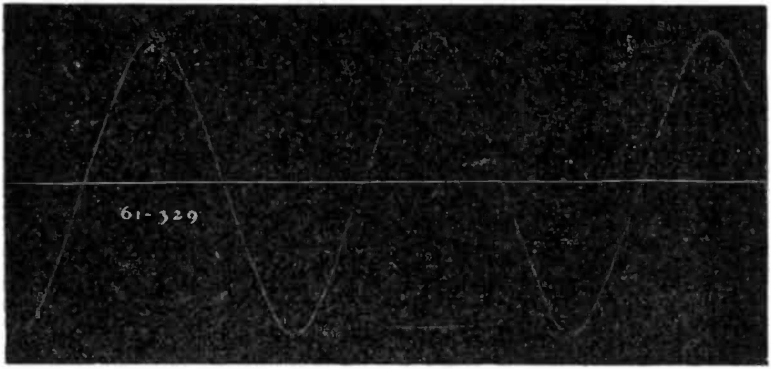
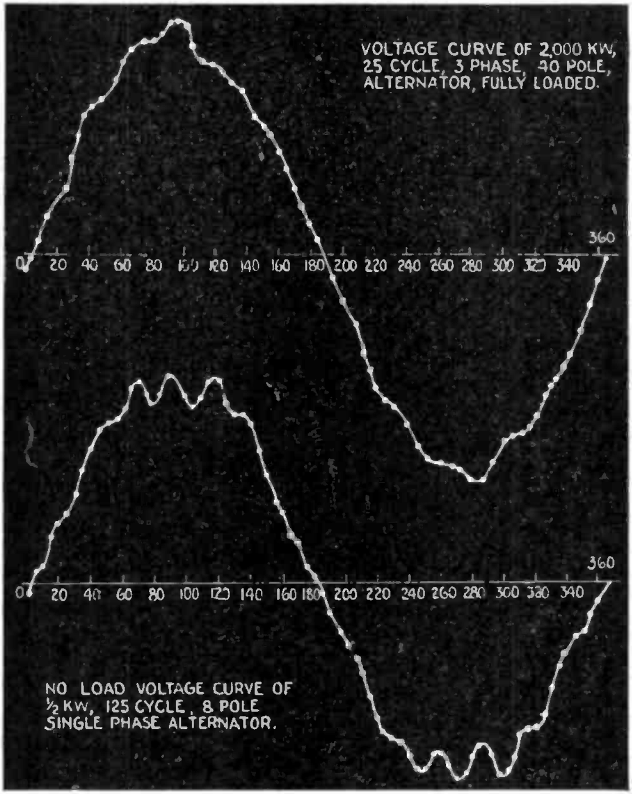


FIG. 1,969 —Reproduction of oscillograph record of Wagner alternator having three coils per phase per pole.

Ans. For three phase, two coils, and for two phase, three coils, per phase per pole.



FIGS. 1,970 and 1,971.—Curves for two alternators; the lower curve represents the wave form of an old style machine. ***In general,*** the shape of the pressure curve is affected by irregular distribution of the magnetic flux. Also, uneven angular velocity of the alternator will distort the wave shape, making it relative to the true curve, lower in the slow spots and higher in the fast ones. Again, the magnetic reluctance of the armature may vary in different angular positions, particularly if the inductors be laid in large slots. This would cause a periodic variation in the reluctance of the whole magnetic circuit and a corresponding pulsation of the total magnetic flux. All these influences operate at open circuit as well as under load. A change in the apparent resistance of the external circuit causes a change in the terminal voltage of the machine. The apparent resistance (impedance) of a circuit to alternating currents depends upon the permeability of the iron adjacent to the circuit. Permeability changes with magnetization.

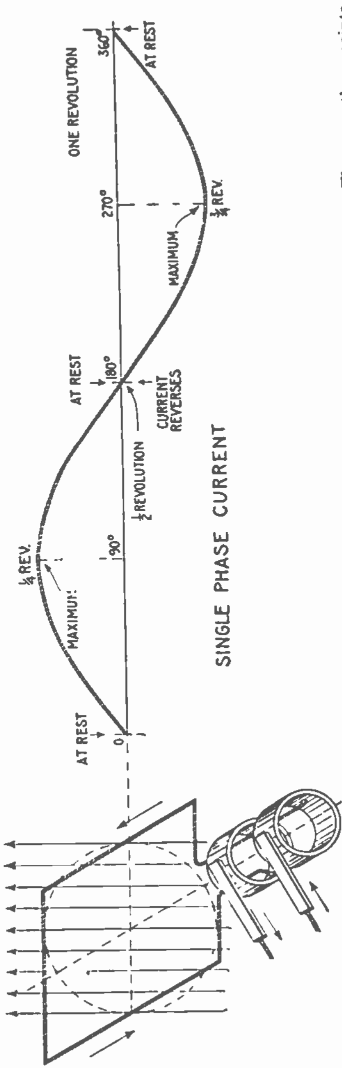


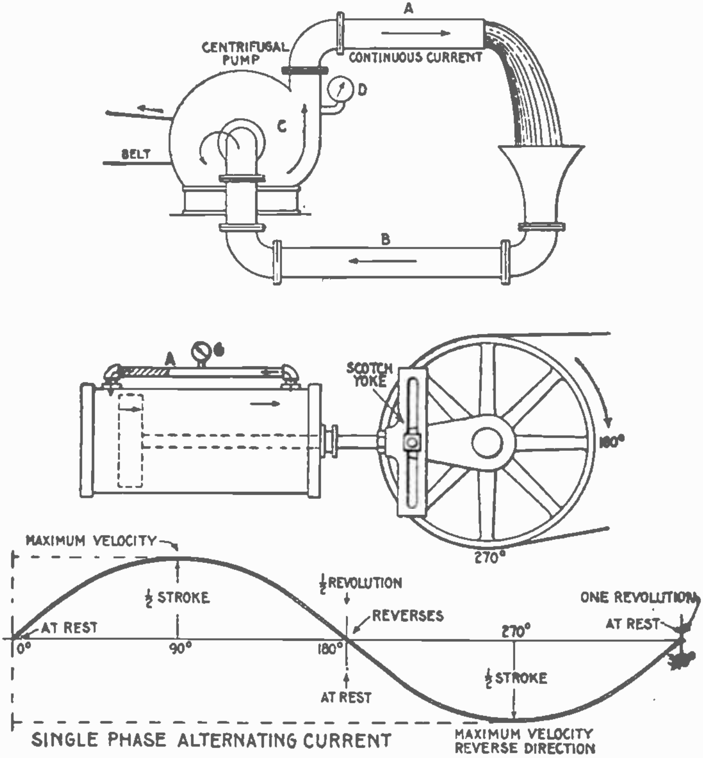
FIG. 1,972.—Elementary one loop alternator and sine curve illustrating single phase alternating current. There are three points during the revolution at which there is no current: at 0° the position shown, 180°, and 360°; in other words, at the beginning, middle point and end of the cycle. The current reaches a maximum at 90°, reverses at 180°, and reaches a maximum in the reverse direction at 270°.

Single or Monophase Current.—This kind of alternating current is generated by an alternator having a single winding on its armature. Two wires, a lead and return, are used as in direct current.

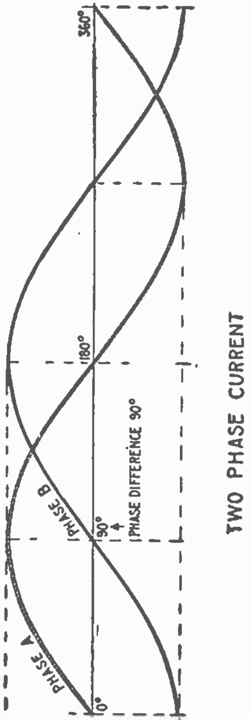
An elementary diagram showing the working principles is shown in fig. 1,972, a similar hydraulic cycle being shown in figs. 1,973 to 1,975.

Two Phase Current.—In most cases two phase current actually consists of two distinct single phase currents flowing in separate circuits. There is often no electrical connection between them; they are of equal period and equal amplitude, but differ in phase by one-quarter of a period.

NOTE.—*Ferraris* in 1888 discovered that a *rotating magnetic field* could be produced by two or more alternating currents displaced in phase from one another. This led to the development of the two and three phase systems.



FIGS. 1,973 to 1,975.—Hydraulic analogy illustrating the difference between *direct* (continuous) and *alternating* current. In fig. 1,973 a centrifugal pump C, forces water to the upper pipe, from which it falls by gravity to the lower pipe B, and re-enters the pump. The current is continuous, always flowing in one direction, that is, it does not reverse its direction. Similarly a direct electric current is constant in direction (does not reverse), though not necessarily constant in value. A direct current, constant in both value and direction as a result of constant pressure, is called "continuous" current. Similarly in the figure the flow is constant, and a gauge D, placed at any point will register a constant pressure, hence the current may be called, in the electrical sense, "continuous." The conditions in fig. 1,974 are quite different. The illustration represents a double acting cylinder with the ends connected by a pipe A, and the piston driven by crank and Scotch yoke as shown. ***In operation,*** if the cylinder and pipe be full of water, a current of water will begin to flow through the pipe in the direction indicated as the piston begins its stroke, increasing to maximum velocity at one-quarter revolution of the crank, decreasing and coming to rest at one-half revolution, then reversing and reaching maximum velocity in the reverse



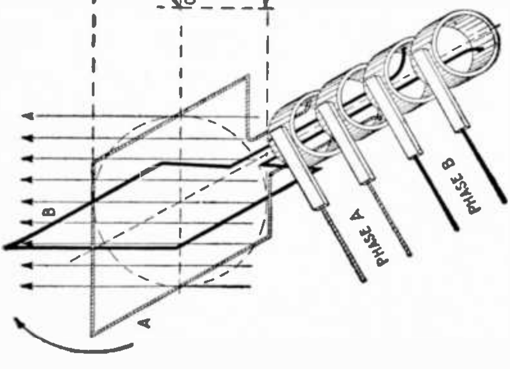


FIG. 1,976.—Elementary two loop alternator and sine curves, illustrating two phase alternating current. If the loops be placed on the alternator armature at 90 magnetic degrees, a single phase current will be generated in each of the windings, the current in one winding being at its maximum value when the other is at zero. In this case four transmission conductors are generally used, two for each separate circuit, and the motors to which the current is led have a double winding corresponding to that on the alternator armature.

With this phase relation one of them will be at a maximum when the other is at zero. Two phase current is illustrated by sine curves in fig. 1,976, and by hydraulic analogy in figs. 1,977 to 1,979.

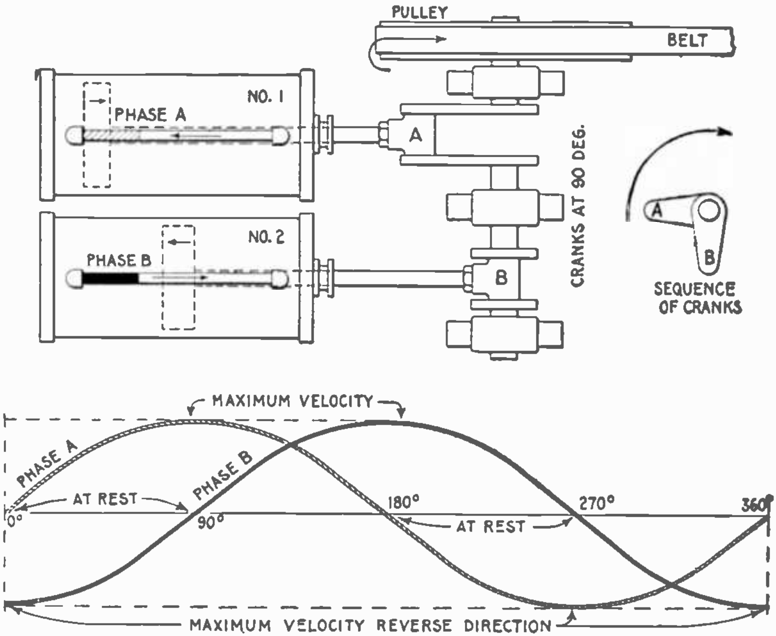
If two identical simple alternators have their armature shafts coupled in such a manner, that when a given armature coil on one is directly under a field pole, the corresponding coil on the other is midway between two poles of its field, the two currents generated will differ in phase by a half alternation, and will be two phase current.

FIGS. 1,973 to 1,975.—*Text continued.*

direction at three-quarter revolution, and coming to rest again at the end of the return stroke. A pressure gauge at G, will register a pressure which varies with the current. Since the alternating electric current undergoes similar changes, the sine curve will apply equally as well to the pump cycle as to the alternating current cycle.

Ques. How must an alternator be constructed to generate two phase current?

Ans. It must have two independent windings, and these must be so spaced out that when the volts generated in one of the two phases are at a maximum, those generated in the other are at zero.



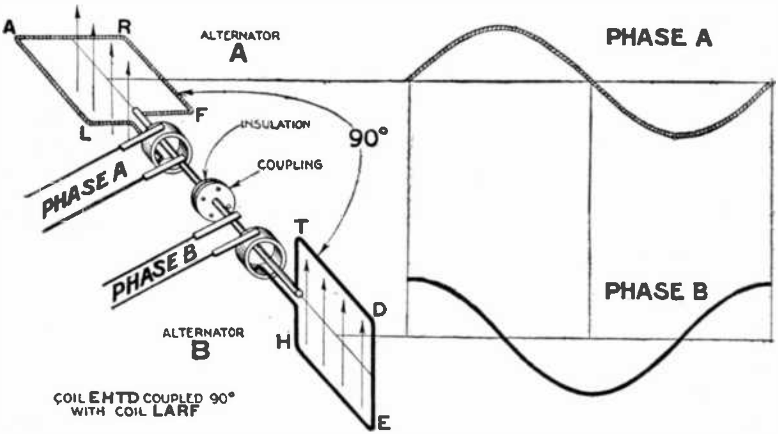
FIGS. 1,977 to 1,979.—Hydraulic analogy illustrating two phase alternating current. In the figure two cylinders, similar to the one in fig. 1,974, are shown, operated from one shaft by crank and Scotch yoke drive. The cranks are at 90° as shown, and the cylinders and connecting pipes full of water. *In operation*, the same cycle of water flow takes place as in fig. 1,974. Since the cranks are at 90°, the second piston is one-half stroke behind the first; the flow of water in No. 1 (phase A) is at a maximum when the flow in No. 2 (phase B) comes to rest, the current conditions in both pipes for the entire cycle being represented by the two sine curves whose phase difference is 90°. Comparing these curves with fig. 1,976, it will be seen that the water and the electric current act in a similar manner.

In other words, the windings, which must be alike, of an equal number of turns, must be displaced along the armature by an angle corresponding to one-quarter of a period, that is, to half the pole pitch.

The windings of the two phases must, of course, be kept separate, hence the armature will have four terminals, or if it be a revolving armature it will have four collector rings.

As must be evident the phase difference may be of any value between 0° and 360°, but in practice it is almost always made 90°.

Ques. In what other way may two phase current be generated?



FIGS. 1,980.—Method of generating two phase alternating current with two single phase alternators coupled with coils at 90° to each other.

Ans. By two single phase alternators coupled to one shaft, as shown in fig. 1,980.

Ques. How many wires are required for two phase distribution?

Ans. A two phase system requires four lines for its distribution; two lines for each phase as in fig. 1,976.

It is possible, but not advisable, to reduce the number to 3, by employing one rather thicker line as a common return for each of the phases as in fig. 1,981.

If this be done, the voltage between the A line and the B line will be equal to $\sqrt{2}$ times the voltage in either phase, and the current in the line used as common return will be $\sqrt{2}$ times as great as the current in either line. assuming the two currents in the two phases to be equal.

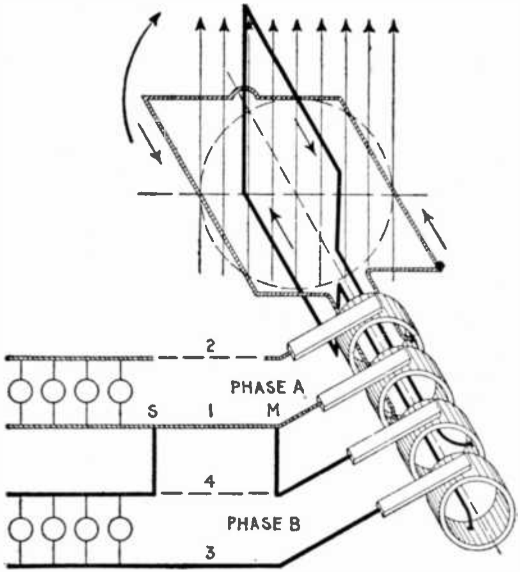


FIG. 1,981.—Diagram of three wire two phase current distribution. In order to save one wire it is possible to use a common return conductor for both circuits, as shown, the dotted portion of one wire 4, being eliminated by connecting across to 1, at M and S. For long lines this is economical, but the interconnection of the circuits increases the chance of trouble from grounds or short circuit. The current in the conductor will be the resultant of the two currents, differing by 90° in phase.

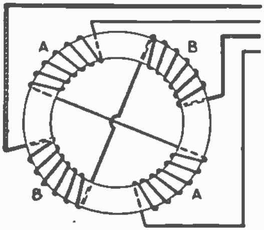
Ques. In what other way may two phase current be distributed?

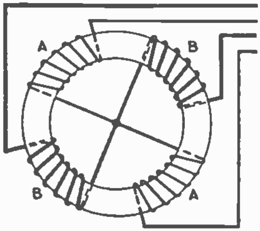
Ans. The mid point of the windings of the two phases may be united in the alternator at a common junction.

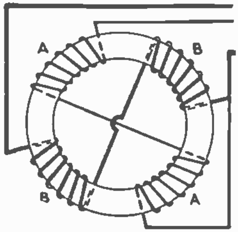
This is equivalent to making the machine into a four phase alternator with half the voltage in each of the four phases, which will then be in successive quadrature with each other.

Ques. How are two phase alternator armatures wound?

Ans. The two circuits may be separate, each having two collector rings, as shown in fig. 1,982, or the two circuits may be coupled at a common middle as in fig. 1,983, or the two circuits may be coupled in the armature so that only three collector rings are required as shown in fig. 1,984.







FIGS. 1,982 to 1,984.—Various two phase armature connections. Fig. 1,982, two separate circuit four collector ring arrangement; fig. 1,983, common middle connection, four collector rings; fig. 1,984, circuit connected in armature for three collector rings. In the figures the black winding represents phase A, and the light winding, phase B.

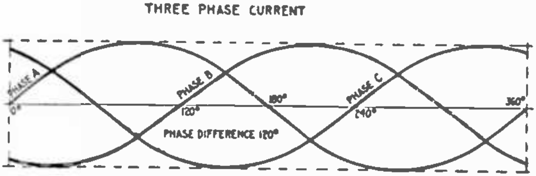
Three Phase Current.—A three phase current consists of three alternating currents of equal frequency and amplitude, but differing in phase from each other by one-third of a period.

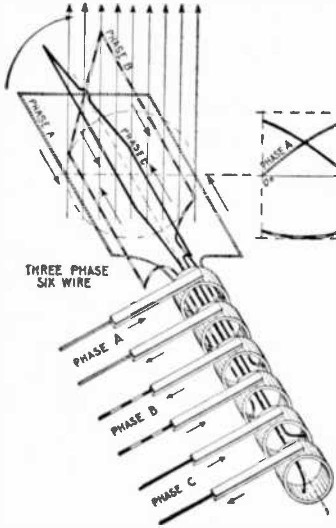
Three phase current as represented by sine curves is shown in fig. 1,986, and by hydraulic analogy in fig. 1,988. Inspection of the figures will show that when any one of the currents is at its maximum, the other two are of half their maximum value, and are flowing in the opposite direction.

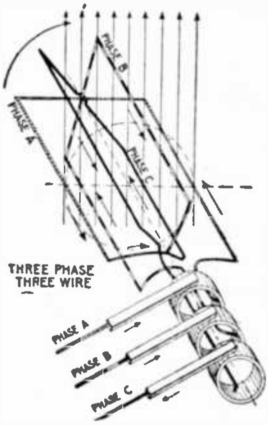
Ques. How is three phase current generated?

Ans. It requires three equal windings on the alternator armature, and they must be spaced out over its surface so as to be successively ⅓ and ⅔ of the period (that is, of the double pole pitch) apart from one another.

Ques. How many wires are used for three phase distribution?





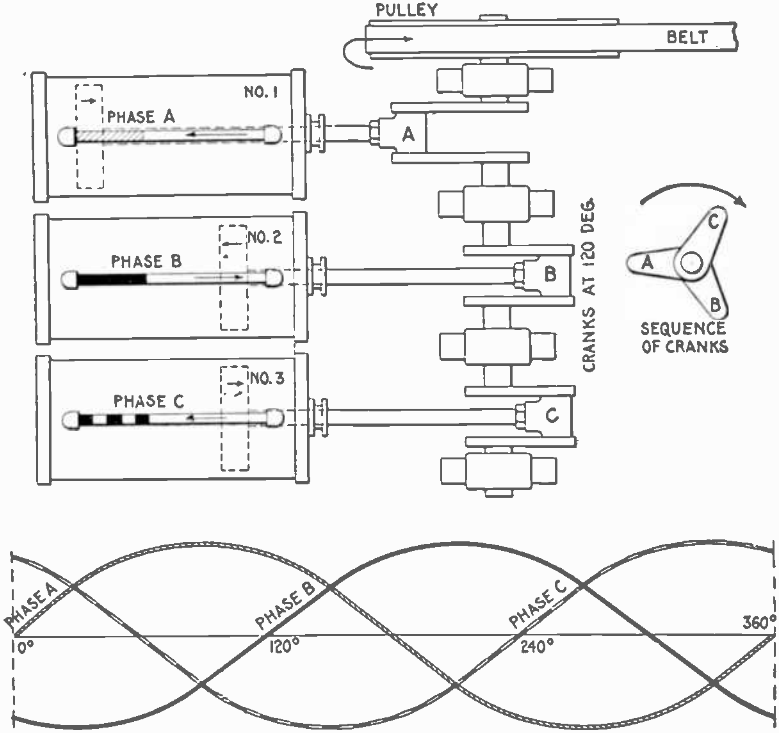


FIGS. 1,985 and 1,986.– Elementary three loop alternator and sine curves, illustrating three phase alternating current. If the loops be placed on the alternator armature at 120 magnetic degrees from one another, the current in each will attain its maximum at a point one-third of a cycle distant from the other two. The arrangement here shown gives three independent single phase currents and requires six wires for their transmission. A better arrangement and the one generally used is shown in fig. 1,987.

FIG. 1,987.—Elementary three wire three phase alternator. For the transmission of three phase current, it is not customary to use six wires, as in fig. 1,985, instead, three ends (one end of each of the loops) are brought together to a common connection as shown (fig. 1,987), and the other ends, connected to the collector rings, giving only three wires for the transmission of the current.

Ans. Either six wires or three wires.

Six wires, as in fig. 1,985, might be used where it is desired to supply entirely independent circuits, or as is more usual only three wires are used as shown in fig. 1,987. In this case it should be observed that if the voltage generated in each one of the three phases separately be E (virtual) volts, the voltage generated between any two of the terminals will be equal to $\sqrt{3} \times E$. Thus, if each of the three phases generate 100 volts, the voltage from the terminal of the A phase to that of the B phase will be 173 volts.



Figs. 1,988 to 1,990.—Hydraulic analogy illustrating three phase alternating current. Three cylinders are here shown with pistons connected through Scotch yokes to cranks placed 120° apart. The same action takes place in each cylinder as in the preceding cases, the only difference being the additional cylinder, and difference in phase relation.

Inductance.—Each time a direct current is started, stopped or varied in strength, the magnetism changes, and induces or tends to induce a pressure in the wire which always has a

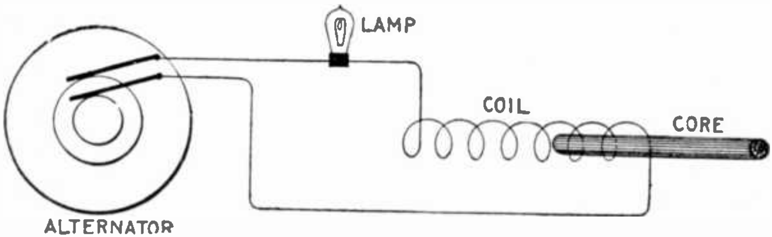


FIG. 1,991.—Experiment illustrating *self-induction* in an alternating current circuit. If an incandescent lamp be connected in series with a coil made of one pound of No. 20 magnet wire, and connected to the circuit, the current through the lamp will be decreased due to the self-induction of the coil. If now an iron core be gradually pushed into the coil, the self-induction will be greatly increased and the lamp will go out, thus showing the great importance which self-induction plays in alternating current work.

FIG. 1,992.—Knott adjustable inductance. *It is made up of* copper wire wound on a threaded hard rubber tube, a construction that has been found to give excellent results both mechanically and electrically. A smooth acting slide permits any desired amount of the wire to be placed in circuit, and a scale on the slide support gives the value of the portion in use. These inductances will be found well suited and convenient to use in connection with high frequency currents and wireless telegraph outfits. Capacity, 1,000 microhenrys.

direction opposing the pressure which originally produced the current. *This self-induced pressure tends to weaken the main current at the start and prolong it when the circuit is opened.*

The expression *inductance* is frequently used in the same sense as *coefficient of self-induction*, which is a quantity pertaining to an electric circuit depending on its geometrical form and the nature of the surrounding medium.

If the direct current maintain the same strength and flow steadily, *there will be no variations in the magnetic field surrounding the wire and no self-induction*, consequently the only retard-

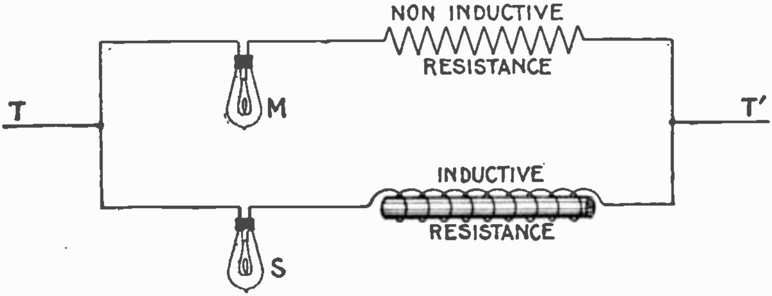


FIG. 1,993.—Non-inductive and inductive resistances. Two currents are shown joined in parallel, one containing a lamp and non-inductive resistance, and the other a lamp and inductive resistance. The two resistances being the same, a sufficient direct pressure applied at T, T′, will cause the lamps to light up equally. If, however, an alternating pressure be applied, M, will burn brightly, while S, will give very little or no light because of the effect of the inductance of the inductive resistance.

ing effect of the current will be the *ohmic "resistance"* of the wire.

If an alternating current be sent through a circuit, there will be two retarding effects:

1. The *ohmic* resistance;
2. The *spurious* resistance.

Ques. Upon what does the ohmic resistance depend?

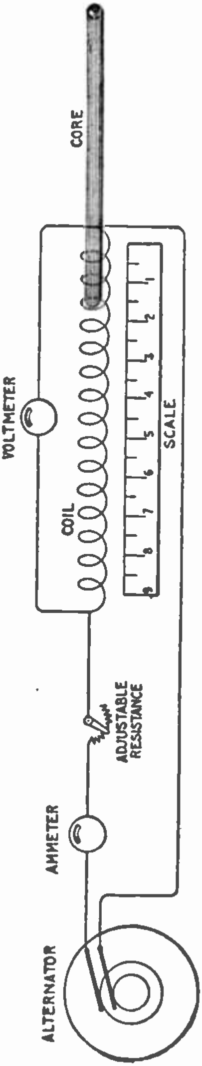


FIG. 1,994.—Inductance test, illustrating the self-induction of a coil which is gradually increased by moving an iron wire core inch by inch into the coil. The current is kept constant with the adjustable resistance throughout the test and readings taken, first without the iron core, and again when the core is put in the coil and moved to the 1, 2, 3, 4, etc., inch marks. By plotting the volt meter readings and the position of the iron core on section paper, a curve is obtained showing graphically the effect of the self-induction. A curve of this kind is shown in fig. 2,062.

Ans. Upon the length, cross sectional area and material of the wire.

Ques. Upon what does the spurious resistance depend?

Ans. Upon the frequency of the alternating current, the shape of the conductor, and nature of the surrounding medium.

Ques. Define inductance.

Ans. It is the total magnetic flux threading the circuit per unit current which flows in the circuit, and which produces the flux.

In this it must be understood that if any portion of the flux thread the circuit more than once, this portion must be added in as many times as it makes linkage.

Inductance, or the coefficient of self-induction, is the capacity which an electric circuit has of producing induction within itself.

Inductance is considered as the ratio between the total induction through a circuit to the current producing it.

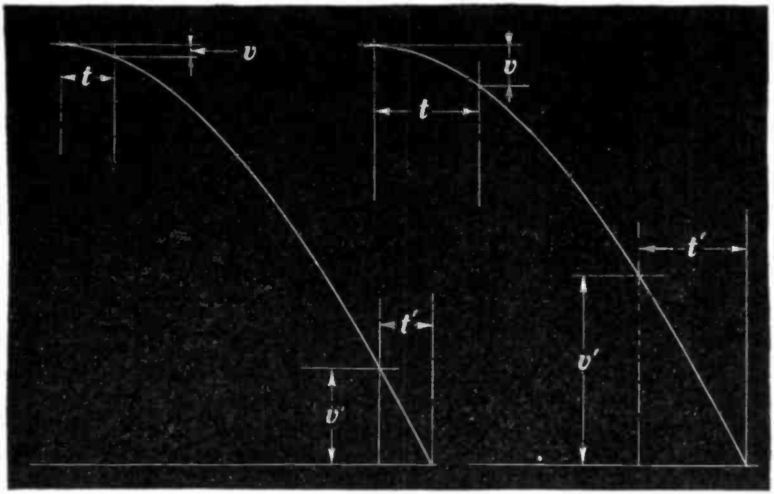
NOTE.—***Inductance.***—The inductance of any circuit depends upon the form of the circuit and the kind of material surrounding the circuit. There is an increase in the value of the inductance of a coil with an increase in the number of turns and an increase in the permeability of the material composing the magnetic circuit.

Ques. What is the unit of inductance?

Ans. The henry.

Ques. Define the henry.

Ans. A coil has an inductance of one henry when the product of the number of lines enclosed by the coil multiplied by



FIGS. 1,995 and 1,996.—Diagrams illustrating inductance in an alternating current circuit. The amount of reverse voltage produced in the circuit depends not only on the inductance of the circuit but also on *the rate at which the current varies*. In fig. 1,995, evidently the rate is least when the current is maximum and greatest when zero, as indicated during the time intervals *t* and *t′*, the current variation for *t* and *t′*, being *v* and *v′*, respectively. If the frequency be doubled as in fig. 1,996, rate of current variation is doubled. This is indicated by taking twice the time intervals *t* and *t′* in fig. 1,996 as in fig. 1,995.

the number of turns in the coil, is equal to 100,000,000 or 10^8 when a current of one ampere is flowing in the coil.

An inductance of one henry exists in a circuit *when a current changing at the rate of one ampere per second induces a pressure of one volt in the circuit.*

Ques. What is the henry called?

Ans. The coefficient of self-induction.

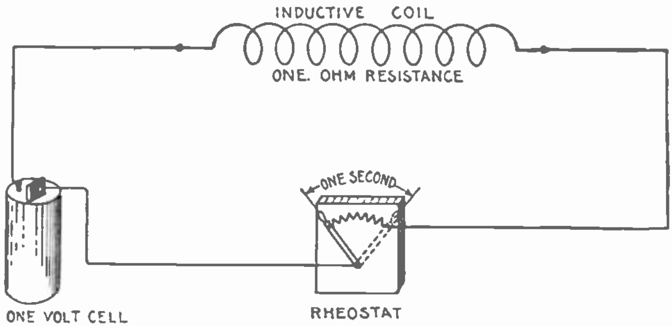
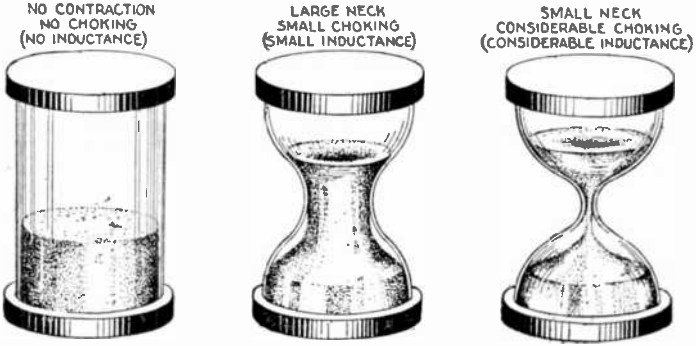


FIG. 1,997.—Diagram illustrating the henry. ***By definition: A circuit has an inductance of one henry when a rate of change of current of one ampere per second induces a pressure of one volt.*** In the diagram it is assumed that the internal resistance of the cell and resistance of the connecting wires are zero.



FIGS. 1,998 to 2,000.—Hour glass analogy of inductance. Fig. 1,998, shows a plain glass cylinder partly filled with sand. Evidently when the glass is inverted the sand will fall to the bottom without any opposition except that due to friction of the glass surface. In fig. 1,999, the sectional area is slightly reduced at the middle section, with result that in addition to the friction (resistance) of the glass surface, opposition (inductance) acts to retard the flow of the sand. In fig. 2,000 the neck is made small resulting in, as is evident, considerable opposition (inductance) to the flow of the current.

The henry is the coefficient by which the time rate of change of the current in the circuit must be multiplied, in order to give the pressure of self-induction in the circuit.

The formula for the henry is as follows:

$$\text{henrys} = \frac{\text{magnetic flux} \times \text{turns}}{\text{current} \times 100{,}000{,}000}$$

or

$$L = \frac{N \times T}{10^8} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

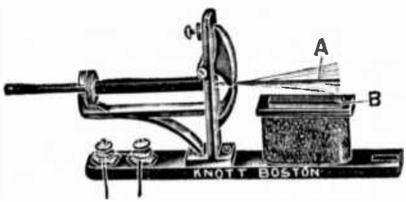


FIG. 2,001.—Knott frequency indicator for 100 volt *a.c.* circuit. This instrument is designed primarily to show on the screen the effect produced by an alternating current on an electro-magnet. The length of the vibrating reed is such as to show clearly on the screen, the ¼-wave length, the ½-wave length and the ¾-wave length. ***In use*** the instrument is connected directly to 110 volt circuit without additional resistance.

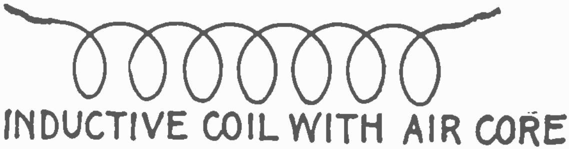
where

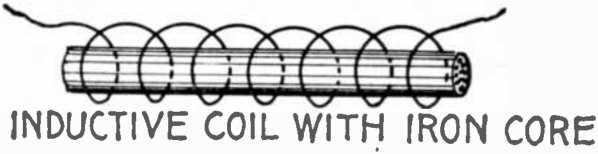
L = coefficient of self induction in henrys;

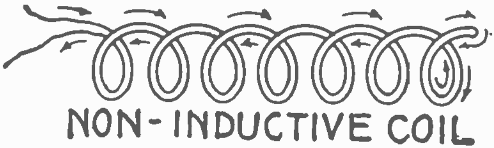
N = total number of lines of force threading a coil when the current is one ampere;

T = number of turns of coil.

If a coil had a coefficient of self-induction of one henry, it would mean that if the coil had one turn, one ampere would set up 100,000,000, or 10^8, lines through it.







FIGS. 2,002 to 2,004.—Various coils. The inductance effect, though perceptible in an air core coil, fig. 2,002, may be greatly intensified by inserting a core made of numerous pieces of iron wire, as in fig. 2,003. Fig. 2,004 shows a non-inductive coil When wound in this manner, a coil will have little or no inductance because each half of the coil neutralizes the magnetic effect of the other This coil, though non-inductive, will have "capacity." It would be useless for solenoids or electro-magnets, as it would have no magnetic field.

NOTE.—*The American physicist, Joseph Henry,* was born in 1798 and died 1878. He was noted for his researches in electromagnetism. He developed the electromagnet, which had been invented by Sturgeon in England, so that it became an instrument of far greater power than before. In 1831, he employed a mile of fine copper wire with an electromagnet, causing the current to attract the armature and strike a bell, thereby establishing the principle employed in modern telegraph practice. He was made a professor at *Princeton* in 1832, and while experimenting at that time, he devised an arrangement of batteries and electromagnets embodying the principle of the telegraph relay which made possible long distance transmission. He was the first to observe magnetic self-induction, and performed important investigations in oscillating electric discharge (1842), and other electrical phenomena. In 1846 he was chosen secretary of the Smithsonian Institution at Washington, an office which he held until his death. As chairman of the U. S. Lighthouse Board, he made important tests in marine signals and lights. In meteorology, terrestrial magnetism, and acoustics, he carried on important researches. Henry enjoyed an international reputation, and is acknowledged to be one of America's greatest scientists.

The henry is too large a unit for use in practical computations, which involves that the millihenry, or $\frac{1}{1,000}$ henry, is the accepted unit.

In pole suspended lines the inductance varies as the metallic resistance,

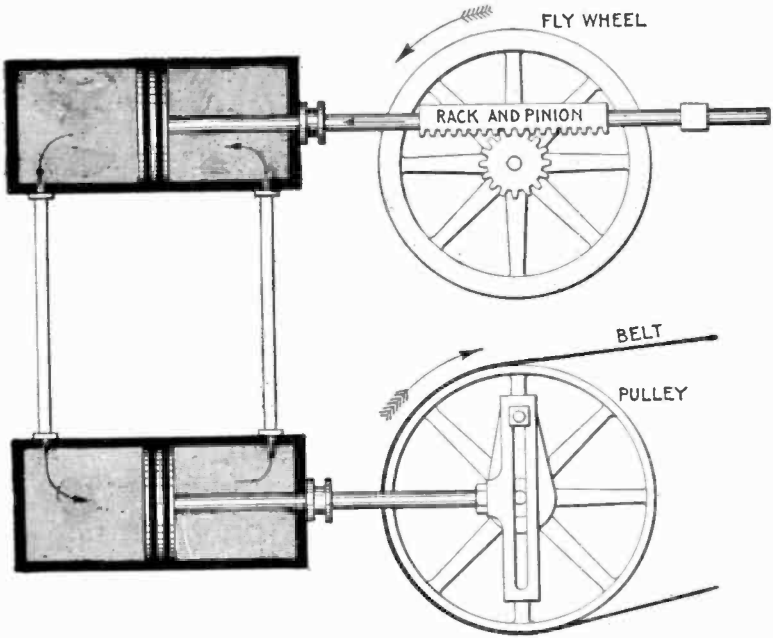


FIG. 2,005.—Hydraulic-mechanical analogy illustrating *inductance* in an alternating current circuit. The two cylinders are connected at their ends by the vertical pipes, each being provided with a piston and the system filled with water. Reciprocating motion is imparted to the lower pulley by Scotch yoke connection with the drive pulley. The upper piston is connected by rack and pinion gear with a fly wheel. ***In operation,*** the to and fro movement of the lower piston produces an alternating flow of water in the upper cylinder which causes the upper piston to move back and forth. The rack and pinion connection with the fly wheel causes the latter to revolve first in one direction, then in the other, in step with the upper piston. The inertia of the fly wheel causes it to resist any change in its state, whether it be at rest or in motion, which is transmitted to the upper piston, causing it to offer resistance to any change in its rate or direction of motion. Inductance in the alternating current circuit has precisely the same effect, that is, *it opposes any change in the strength or direction of the current.*

the distance between the wires on the cross arm and the number of cycles per second, as indicated by accepted tables. Thus, for one mile of No. 8 B. & S. copper wire, with a resistance of 3,406 ohms, the coefficient of self-induction with 6 inches between centers is .00153, and, with 12 inches, .00175.

Ques. How does the inductance of a coil vary with respect to the core?

Ans. It is least with an air core; with an iron core, it is greater in proportion to the permeability* of the iron.

The coefficient L for a given coil is a constant quantity so long as the

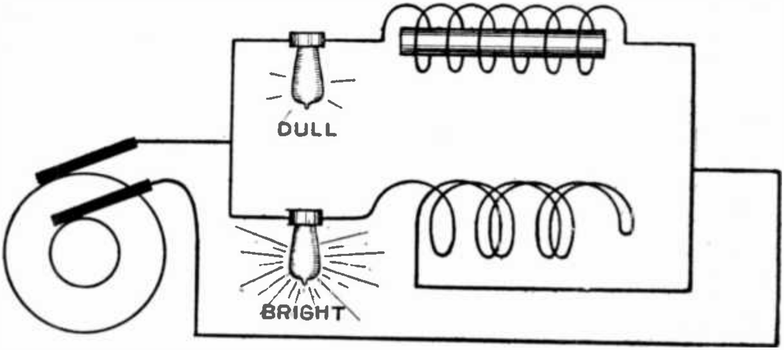


FIG. 2,003.—Effect of inductive and non-inductive coils in an alternating current circuit. When the current is on, the lamp in series with the inductive coil will be dimly lighted while the other lamp in series with the non-inductive coil will give a bright light. The reason for this difference is because of the opposition offered by the inductive coil to the current. That is, each coil has the same ohmic resistance, but the inductive coil has in addition the spurious resistance due to inductance, hence it shunts less current from the lamp than does the non-inductive coil.

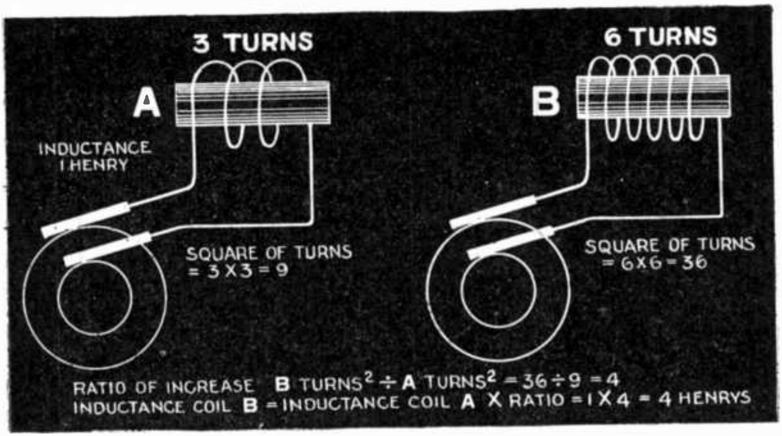
magnetic permeability of the material surrounding the coil does not change. This is the case where the coil is surrounded by air. When iron is present, the coefficient L is practically constant, provided the magnetism is not forced too high.

*NOTE.—The permeability of iron varies from 500 to 1,000 or more. The permeability of a given sample of iron is not constant, but decreases in value as the magnetizing force increases. Therefore the inductance of a coil having an iron core is not a constant quantity as is the inductance of an air core coil.

In most cases arising in practice, the coefficient L, may be considered to be a constant quantity, just as the resistance R, is usually considered constant. The coefficient L, of a coil or circuit is often spoken of as its *inductance*.

Ques. Why is the iron core of an inductive coil made with a number of small wires instead of one large rod?

Ans. It is laminated in order to reduce eddy currents and consequent loss of energy, and to prevent excessive heating of the core.



FIGS. 2,007 and 2,008.—Diagrams illustrating relation of number of turns of an inductive coil and the inductances.

Ques. How does the number of turns of a coil affect the inductance?

Ans. The inductance varies as the square of the turns, as illustrated in figs. 2,007 and 2,008.

That is, if the turns be doubled, the inductance becomes four times as great.

The inductance of a coil is easily calculated from the following formulæ:

$$L = 4\pi^2 r^2 n^2 \div (l \times 10^9) \dots\dots\dots\dots\dots (1)$$

for a thin coil with air core, and

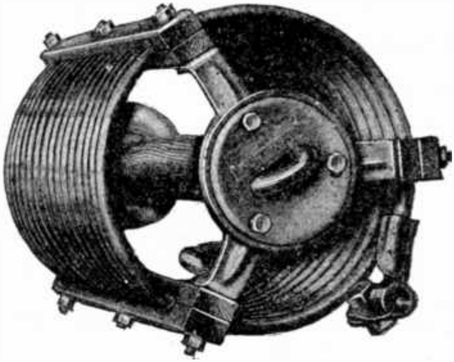


FIG. 2,009.—General Electric 400 ampere suspension copper choke coil. *The copper coil* has the advantage over other materials of being practically non-corrosive and non-crystalizing. The coils with braces and end spiders are interchangeable in all mountings, for the same ampere capacity. The turns are separated from one another and braced, the braces being held by end spiders. Weight of coil proper is supported on end spiders.

NOTE.—By definition a *choke coil* is *a coil with large inductance and small resistance, used to impede alternating currents.* The choke coil or coil of the character just described is used extensively as an auxiliary to the lightning arrester. In this connection the primary objects of the choke coil should be: 1, to hold back the lightning disturbance from the transformer or alternator until the lightning arrester discharges to earth. If there be no lightning arrester the choke coil evidently cannot perform this function. 2, to lower the frequency of the oscillation so that whatever charge gets through the choke coil will be of a frequency too low to cause a serious drop of pressure around the first turns of the end coil in either alternator or transformer. Another way of expressing this is from the standpoint of wave front: a steep wave front piles up the pressure when it meets an inductance. The second function of the choke coil is, then, to smooth out the wave front of the surge. The principal electrical condition to be avoided is that of resonance. The coil should be so arranged that if continual surges be set up in the circuit, a resonant voltage due to the presence of the choke coil cannot build up at the transformer or alternator terminals. In the types shown above, the hour glass coil has the following advantages on high voltages: 1, should there be any arcing between adjacent turns the coils will reinsulate themselves; 2, they are mechanically strong, and sagging is prevented by tapering the coils toward the center turns; 3, the insulating supports can be best designed for the strains which they have to withstand. Choke coils should not be used in connection with cable systems.

$$L = 4\pi^2 r^2 n^2 \mu \div (l \times 10^9) \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

for a coil having an iron core. In the above formulæ:

L = inductance in henrys;
π = 3.1416;
r = average radius of coil in centimeters;
n = number of turns of wire in coil;
μ = permeability of iron core;
l = length of coil in centimeters.

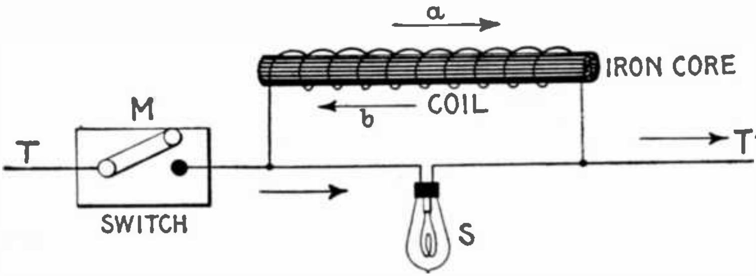


FIG. 2,010.—Inductance experiment with intermittent direct current. A lamp S, is connected in parallel with a coil of fairly fine wire having a removable iron core, and the terminals T, T', connected to a source of direct current, a switch M, being provided to interrupt the current. The voltage of the current and resistance of the coil are of such values that when a steady current is flowing, the lamp filament is just perceptibly red. *At the instant of making the circuit, the lamp will momentarily glow more brightly than when the current is steady; on breaking the circuit the lamp will momentarily flash with great brightness.* In the first case, the reverse pressure, due to inductance, as indicated by arrow *b*, will momentarily oppose the normal pressure in the coil, so that the voltage at the lamp will be momentarily increased, and will consequently send a momentarily stronger current through the lamp. On breaking the main circuit at M, the field of the coil will collapse, generating a momentary much greater voltage than in the first instance, in the direction of arrow *a*, the lamp will flash up brightly in consequence.

Example.—An air core coil has an average radius of 10 centimeters and is 20 centimeters long, there being 500 turns, what is the inductance?

Substituting these values in formula (1)

$$L = 4 \times (3.1416)^2 \times 10^2 \times 500^2 \div (20 \times 10^9) = .00494 \text{ henry.}$$

Ques. Is the answer in the above example in the customary form?

Ans. No; the henry being a very large unit, it is usual to express inductance in thousandths of a henry, that is, in *milli-henrys*. The answer then would be $.04935 \times 1,000 = 49.35$ milli-henrys.

Example.—An air core coil has an inductance of 50 milli-henrys; if an iron core, having a permeability of 600 be inserted, what is the inductance?

The inductance of the air core coil will be multiplied by the permeability of the iron; the inductance then is increased to

$$50 \times 600 = 30{,}000 \text{ milli-henrys, or } 30 \text{ henrys.}$$

Ohmic Value of Inductance.—The rate of change of an alternating current at any point expressed in degrees is equal to the product of 2π *multiplied by the frequency, the maximum current, and the cosine of the angle of position* θ; that is (using symbols)

$$\text{rate of change} = 2\pi f I_{max} \cos \theta.$$

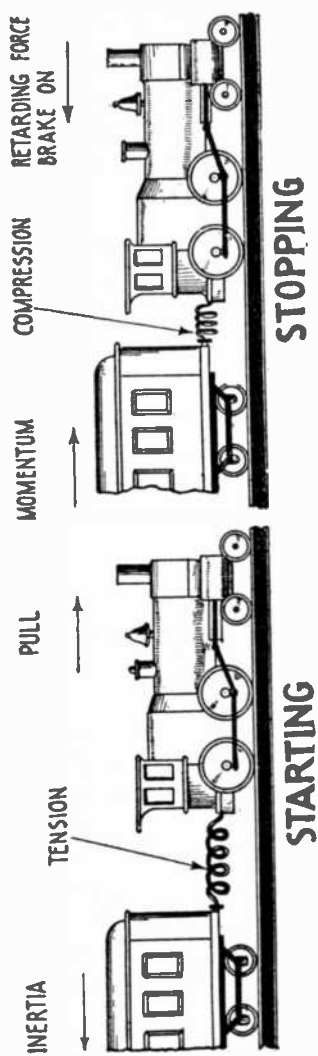
The numerical value of the rate of change is independent of its positive or negative sign, so that the sign of the $\cos \phi$ is disregarded.

The period of greatest rate of change is that at which $\cos \phi$ has the greatest value, and the maximum value of a cosine is when the arc has a value of zero degrees or of 180 degrees, its value corresponding, being 1. (See fig. 2,074, page 1,464.)

The pressure due to inductance is equal to the product of the rate of change by the inductance; that is, calling the inductance L, the pressure due to it at the point of maximum value or

$$E_{max} = 2\pi f I_{max} \times L \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Now by Ohm's law



FIGS. 2,011 and 2,012.—Mechanical analogy of self-induction in an *a.c.* circuit. *In starting,* the locomotive first moves and stretches the spring before the car begins to move, thus producing an initial force necessary to overcome the opposition or inertia of matter which resists the effort to change it from a state of rest to a state of motion. *In stopping,* the opposite conditions obtain. *Similarly,* like conditions are present each time electricity is set in motion or brought to rest. This opposition is visibly presented on opening a switch, the current momentarily *arcing the gap,* against the enormous resistance thus introduced.

$$E_{max} = RI_{max} \ldots\ldots (2)$$

for a current I_{max}, hence substituting equation (2) in equation (1)

$$RI_{max} = 2\pi f\ I_{max} \times L$$

from which, dividing both sides by I_{max}, and using X_i for R

$$X_i = 2\pi f L \ldots\ldots (3)$$

which is the ***ohmic equivalent of inductance.***

NOTE.—*Inductance* at the instant voltage begins to act upon an inductive circuit is the only opposing factor, because until a current is flowing resistance is without effect. The necessary condition of equilibrium is brought about by the creation of a reverse pressure equal to the impressed, and this reverse pressure is equal to the product of the inductance by the rate of change of current intensity.

NOTE.—After a current has begun to flow a part of the voltage equal to the product of this current by the resistance is expended in maintaining the current and this amount is the RI drop; the rest of the voltage produces an increase of current whose rate of increase or of change is such as to produce a reverse pressure exactly equal to the residual voltage. Knowing the inductance and the residual voltage the rate of change = voltage ÷ inductance.

The frequency of a current being the number of periods or waves per second, then, if T = the time of a period, the frequency of a current may be obtained by dividing 1 second by the time of a period; that is

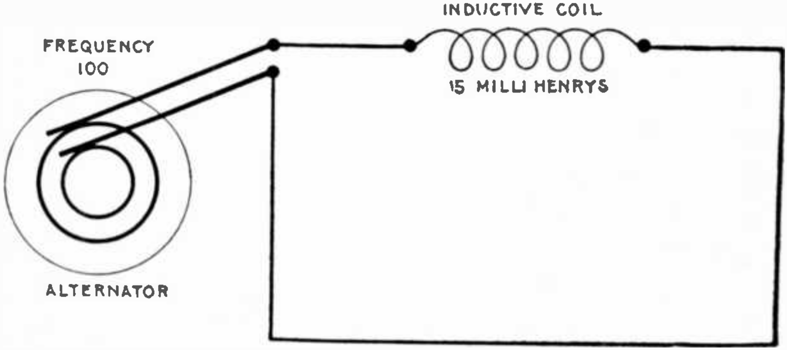


FIG. 2,013.—Diagram showing alternating circuit containing inductance. Formula for calculating the ohmic value of inductance or "inductance reactance" is $X_i = 2\pi f L$ in which X_i = inductance reactance; π = 3.1416; f = frequency; L = inductance *in henrys* (not millihenrys). L = 15 millihenrys = 15 ÷ 1000 = .015 henrys. Substituting, $X_i = 2 \times 3.1416 \times 100 \times .015 = 9.42$ ohms.

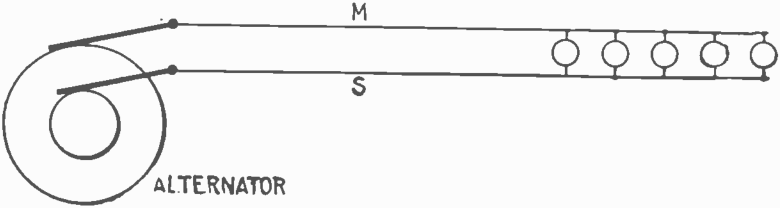


FIG. 2,014.—Diagram illustrating effect of capacity in an alternating circuit. Considering its action during one cycle of the current, the alternator first "pumps," say from M to S; electricity will be heaped up, so to speak, on S, and a deficit left on M, that is, S will be + and M −. If the alternator be now suddenly stopped, there would be a momentary return flow of electricity from S to M, through the alternator. If the alternator go on working, however, it is obvious that the electricity heaped up on S, helps or increases the flow when the alternator begins to pump from S, to M, in the second half of the cycle, and when the alternator again reverses its pressure, the + charge on M, flows round to S, and helps the ordinary current. The above circuit is not strictly analogous to the insulated plates of a condenser, but, as is verified in practice, that with a rapidly alternating pressure, the condenser action is not perceptibly affected if the cables be connected across by some non-inductive resistance as for instance incandescent lamps.

$$\text{frequency} = \frac{\text{one second}}{\text{time of one period}} = \frac{1}{T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

substituting $\frac{1}{T}$ for f in equation (3)

$$X_i = 2\,\pi\,\frac{L}{T}$$

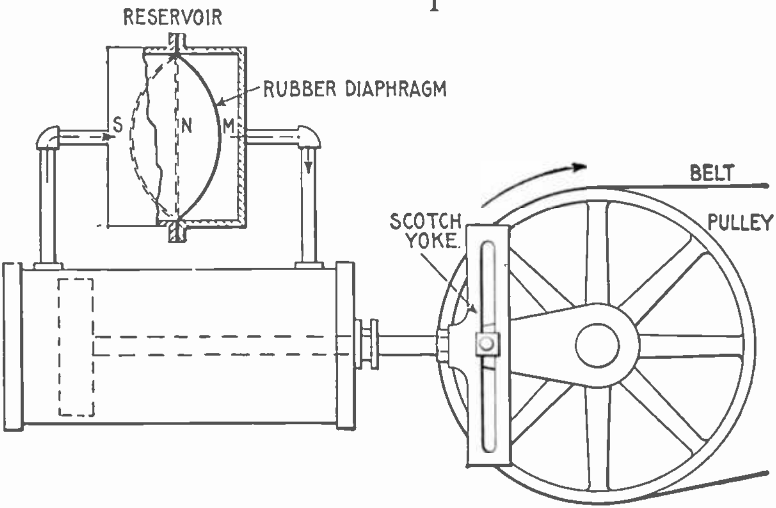


FIG. 2,015.—Hydraulic analogy illustrating capacity in an alternating current circuit. A chamber containing a rubber diaphragm is connected to a double acting cylinder and the system filled with water. *In operation*, as the piston moves, say to the left from the center, the diaphragm is displaced from its neutral position N, and stretched to some position M, in so doing offering increasing resistance to the flow of water. On the return stroke the flow is reversed and is assisted by the diaphragm during the first half of the stroke, and opposed during the second half. The diaphragm thus acts with the flow of water one-half of the time and in opposition to it one-half of the time. This corresponds to the electrical pressure at the terminals of a condenser connected in an alternating current circuit, and it has a maximum value when the current is zero and a zero value when the current is a maximum.

Capacity.—When an electric pressure is applied to a condenser, the current plays in and out, charging the condenser in alternate directions. As the current runs in at one side and out at the other, the dielectric becomes charged, and tries to discharge itself by setting up an opposing electric pressure. This opposing pressure rises just as the charge increases.

A mechanical analogy is afforded by the bending of a spring, as in fig. 2,016, which, as it is being bent, exerts an opposing force equal to that applied, provided the latter do not exceed the capacity of the spring.

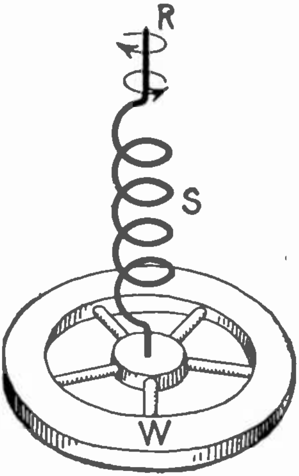
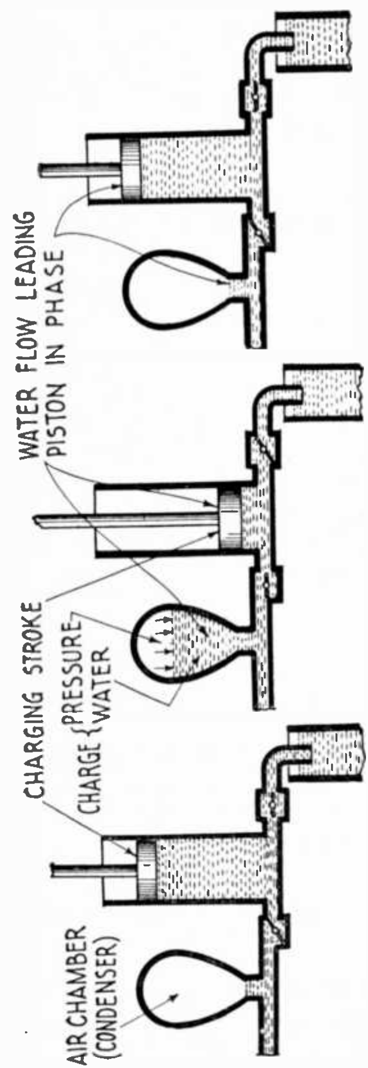


FIG. 2,016.—Mechanical analogy illustrating effect of capacity in an alternating circuit. If an alternating twisting force be applied to the top R, of the spring S, the action of the latter may be taken to represent capacity, and the rotation of the wheel W, alternating current. The twisting force (impressed pressure) must first be applied *before* the rotation of W, (current) will begin. The resiliency or rebounding effect of the spring will, in time, cause the wheel W, to move (amperes) in advance of the twisting force (voltage), thus representing the current *leading in phase*.

Ques. What is the effect of capacity in an alternating circuit?

Ans. It is exactly opposite to that of inductance, that is, it assists the current to rise to its maximum value sooner than it would otherwise.



FIGS. 2,017 to 2,019.—Hydraulic analogy of *capacity*. The pressure pump on the down stroke (figs. 2,017 and 2,018) forces (*impressed pressure*) the water into the air chamber (*condenser*) charging it against an increasing back pressure, which, at the end of the stroke is *in excess* of the pressure due to the head (*resistance*) pumped against. This accumulation of pressure in the air chamber keeps the water (*current*) flowing while the piston is on the return stroke (figs. 2,018 and 2,019), and the impressed pressure (volts) is zero, the *water flow* (current) *leading* in phase the power stroke (*volts*) of the pump.

Ques. Is it necessary to have a continuous metallic circuit for an alternating current?

Ans. No, it is possible for an alternating current to flow through a circuit which is divided at some point by insulating material.

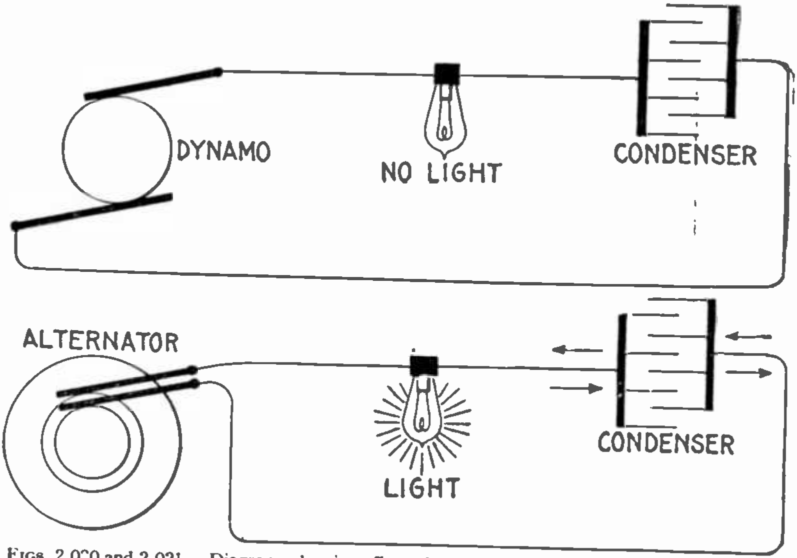
Ques. How can the current flow under such condition?

Ans. Its flow depends on the capacity of the circuit and accordingly a condenser may be inserted in the circuit as in fig. 2,021, thus interposing an insulated gap, yet permitting an alternating flow in the metallic portion of the circuit.

NOTE.—***The term "farad"*** is a contraction of Faraday, the name of the distinguished English scientist. He was born 1791, died 1867.

Ques. Name the unit of capacity and define it.

Ans. The unit of capacity is called the *farad* and its symbol is C. A condenser is said to have a capacity of one farad if



FIGS. 2,020 and 2,021.—Diagrams showing effect of condenser in direct and alternating current circuits. Each circuit contains an incandescent lamp and a condenser, one circuit connected to a dynamo and the other to an alternator. Since the condenser interposes a gap in the circuit, evidently in fig. 2,020 no current will flow. In the case of alternating current, fig. 2,021, the condenser gap does not hinder the flow of current in the metallic portion of the circuit. In fact the alternator produces a continual surging of electricity backward and forward from the plates of the condenser around the metallic portion of the circuit, similar to the surging of waves against a bulkhead which projects into the ocean. (It should be understood that the electric current ceases at the condenser, there being no flow between the plates.)

one coulomb (that is, one ampere flowing one second), when stored on the plates of the condenser will cause a pressure of one volt across its terminals.

The farad being a very large unit, the capacities ordinarily encountered in practice are expressed in millionths of a farad, that is, in *microfarads* —a capacity equal to about three miles of an Atlantic cable.

It should be noted that the microfarad is used only for convenience, and that *in working out problems, capacity should always be expressed in farads before substituting in formulæ,* because the farad is chosen with respect to the volt and ampere,

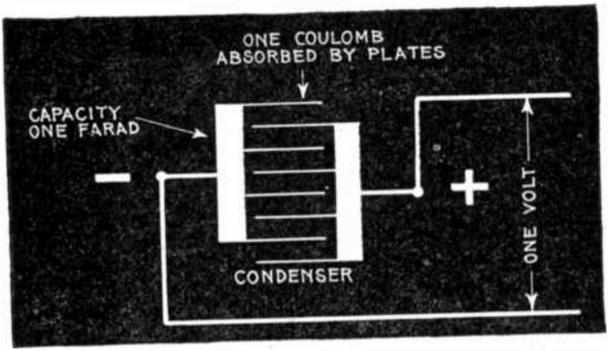


FIG. 2,022.—Diagram illustrating a *farad*. A condenser is said to have a capacity of one farad if it will absorb one coulomb of electricity when subjected to a pressure of one volt. The farad is a very large unit, and accordingly the microfarad or one millionth of a farad is often used, though *this must be reduced to farads before substituting in formulæ.*

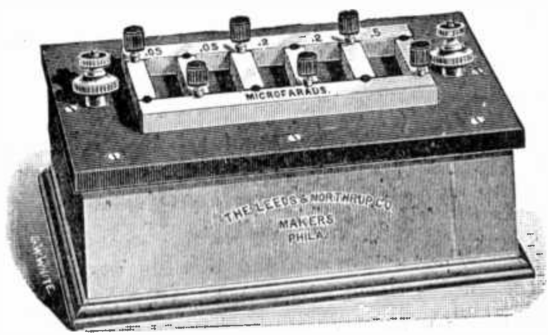


FIG. 2,023.—Condenser of one microfarad capacity. It is subdivided into five sections of .5, .2, .2, .05 and .05 microfarad. The plates are mounted between and carried by lateral brass bars which are fastened to a hard rubber top. Each pair of condenser terminals is fastened to small binding posts mounted on hard rubber insulated posts.

as defined on page 1,425 and hence must be used in formulæ along with these units.

For instance, a capacity of 8 microfarads as given in a problem would be substituted in a formula as .000008 of a farad.

The charge Q, forced into a condenser by a steady electric pressure E, is

$$Q = EC$$

in which

Q = charge in coulombs.

FIG. 2,024 and 2,025.—Knott variable air condenser. Capacity, .001 *mf*. *In construction*, the vanes are of aluminum and the moving system works without interference of the plates or other objectionable features commonly met with in instruments of cheaper construction. The top is of hard rubber. A binding post is provided connecting to the case for grounding in experiments where the utmost accuracy is required. These condensers will be found of great usefulness in radio and in experiments with currents of high frequency.

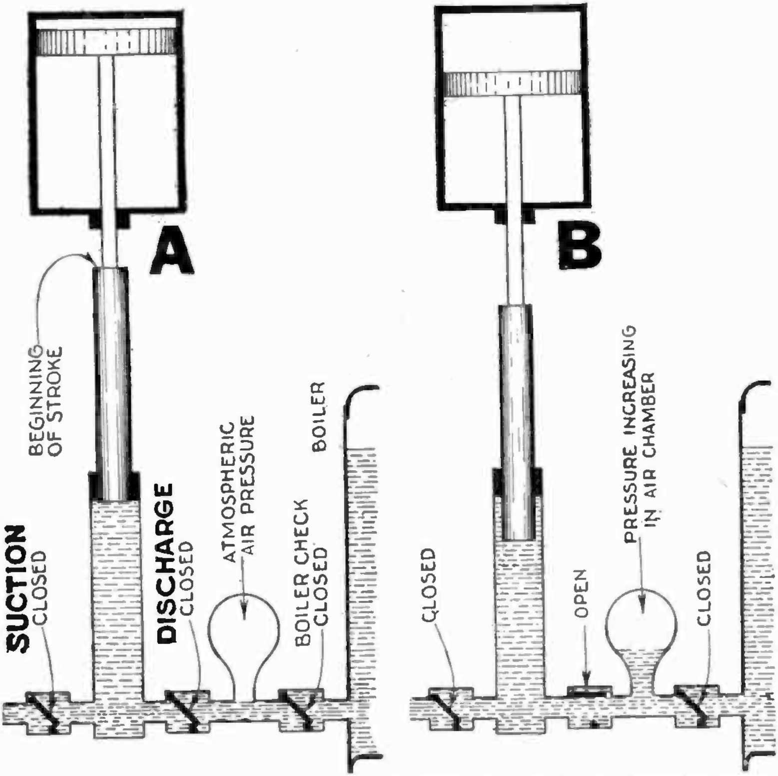
E = electric pressure in volts;
C = capacity of condenser in farads.

Ques. What is the material between the plates of a condenser called?

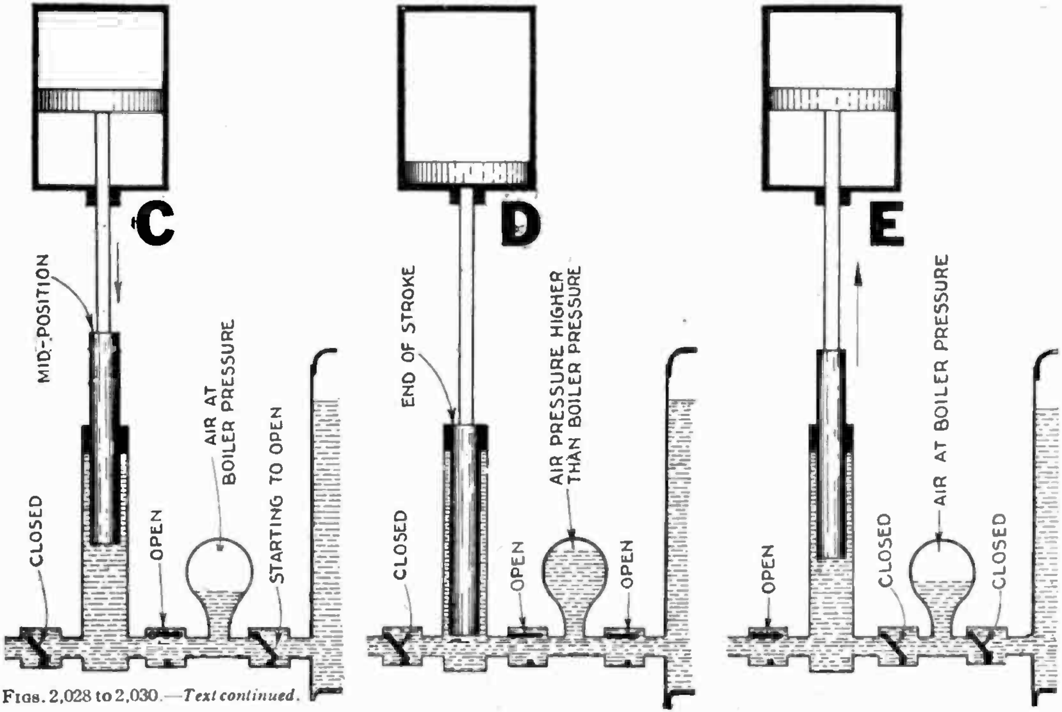
Ans. The *dielectric*.

Ques. Upon what does the capacity of a condenser depend?

Ans. It is proportional to the area of the plates, and inversely proportional to the thickness of the dielectric between



FIGS. 2,026 and 2,027.—Pneumatic analogy illustrating capacity in an alternating current circuit. The illustrations show the cycle of operation of a single acting boiler feed pump fitted with air chamber. *In operation*, as the plunger starts its downward stroke, fig. **A**, water starts flowing (amperes) into air chamber at maximum rate, the water pressure (impressed voltage) starting at zero. As the plunger continues on its stroke, fig. **B**, it encounters increasing opposition or reverse pressure due to water flowing into air chamber (condenser) and compressing the air. At the instant shown in fig. **C**, the pressure in the air chamber has become equal to the boiler pressure; discharge check is on point of opening to admit water to boiler. Fig. **D**, shows excess air pressure at end of stroke. Here the



FIGS. 2,028 to 2,030.—*Text continued.*

extra pressure produces a capacity effect in forcing water into the boiler although the impressed pressure is for the instant discontinued. The flow continues until the boiler and condenser pressures become equalized as in fig. **E**. The analogy is further explained by the curves fig. 2,031.

the plates, a correction being required unless the thickness of the dielectric be very small as compared with the dimensions of the plates.

The capacity of a condenser is also proportional to the *specific inductive capacity* of the dielectric between the plates of the condenser.

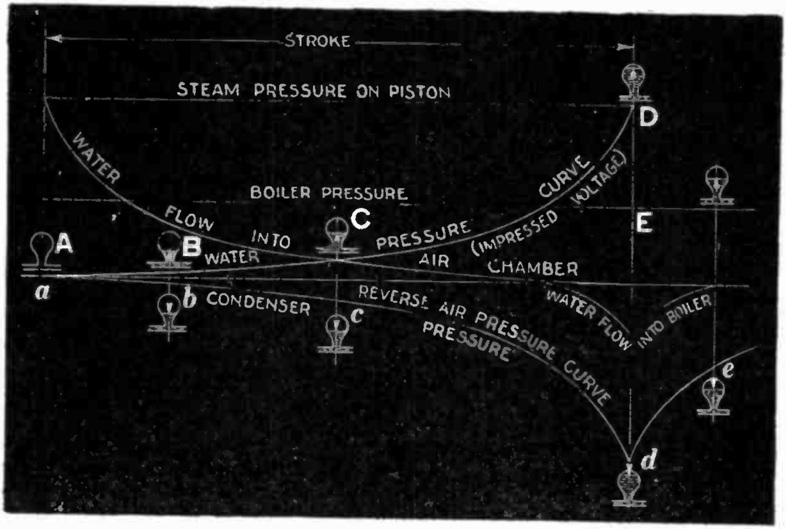


FIG. 2,031.—Pressure and flow curves illustrating boiler feed pump analogy of alternating current. If constant steam pressure be applied to the piston, it will start at **A**, with maximum velocity, and with the increasing water pressure indicated by the curve **ABCD**, which balances the increasing air pressure (*abcd*) the speed will gradually decrease to zero at the end of the stroke at which point the water pressure **D**, equals steam pressure, thus the water flow (amperes) is maximum where the air pressure (condenser pressure) is zero, and zero where the pressure is maximum at end of stroke. At this instant water flows into boiler due to the excess air pressure forcing water from air chamber and continues flowing with decreasing velocity until the pressure in air chamber becomes the same as that in the boiler as at **E**, at which instant the flow ceases.

Specific Inductive Capacity.—Faraday discovered that different substances have different powers of carrying lines of electric force.

Thus the charge of two conductors having a given difference of pressure between them depends on the medium between them as well as on their size and shape. The number indicating the magnitude of this property of the medium is called its *specific inductive capacity*, or *dielectric constant*.

The specific inductive capacity of air, which is nearly the same as that of a vacuum, is taken as unity. In terms of this unit, the following are some typical values of the dielectric constant: Water 80, glass 6 to 10, mica 6.7, gutta percha 3, india rubber 2.5, paraffin wax 2, ebonite 2.5, castor oil 4.8.

In underground cables for very high pressures, the insulation, if homogeneous throughout, would have to be of very great thickness in order to have sufficient dielectric strength. By employing material of high specific inductive capacity close to the conductor, and material of lower specific inductive capacity toward the outside, that is, by *grading* the

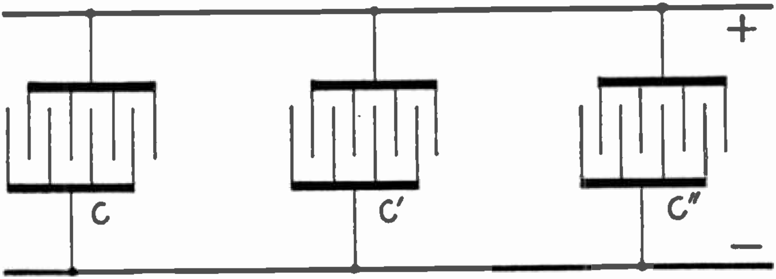


FIG. 2,032.—Parallel connection of condensers. Like terminals are joined together. The capacity of such arrangement is equal to *the sum of the respective capacities*, that is C = c+c′+c″.

insulation, a considerably less total thickness affords equally high dielectric strength.

Ques. How are capacity tests usually made?

Ans. By the aid of standard condensers.

Ques. How are condensers connected?

Ans. They may be connected in parallel as in fig. 2,032, or in series (cascade) as in fig. 2,033.

Condensers are now constructed so that the two methods of arranging the plates may conveniently be combined in one condenser, thereby obtaining a wider range of capacity.

Ques. How may the capacity of a condenser, wire, or cable be tested?

Ans. This may be done by the aid of a standard condenser, trigger key, and an astatic or ballistic galvanometer.

In making the test, first obtain a "constant" by noting the deflection *d*, due to the discharge of the standard condenser after a charge of, say, 10 seconds from a given voltage. Then discharge the other condenser,

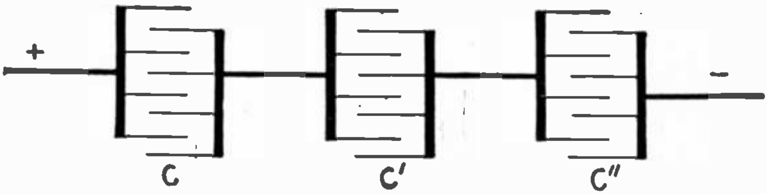


FIG. 2,033.—Series or cascade connection of condensers. Unlike terminals are joined together as shown. The total capacity of such connection is equal to *the reciprocal of the sum of the reciprocals of the several capacities*, that is, $C = 1 \div \left(\frac{1}{c} + \frac{1}{c'} + \frac{1}{c''}\right)$

wire, or cable through the galvanometer after 10 seconds charge, and note the deflection d'. The capacity C′, of the latter is then

$$C' = C \times \frac{d'}{d}$$

in which C, is the capacity of the standard condenser.

Ohmic Value of Capacity.—The capacity of an alternating current circuit is *the measure of the amount of electricity held by it when its terminals are at unit difference of pressure.* Every such circuit acts as a condenser.

If an alternating circuit, having no capacity, be opened, no current can be produced in it, but if there be capacity at the break, current may be produced as in fig. 2,021.

The action of capacity referred to the current wave is as follows: As the wave starts from zero value and rises to its maximum value, the current is due to the discharge of the capacity, which would be represented by a condenser. In the case of a sine current, the period required for the current to pass from zero value to maximum is one-quarter of a cycle.

At the beginning of the cycle, the condenser is charged to the maximum amount it receives in the operation of the circuit.

At the end of the quarter cycle when the current is of maximum value, the condenser is completely discharged.

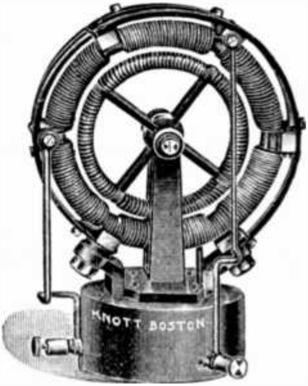


FIG. 2,034.—Knott alternating current demonstration apparatus; *three phase Tesla motor*. This motor is wound for use on a pressure of not over 4 volts. The windings are made of three colors of wires and there are six fields with a short circuited rotor. All connections are open and are connected in star and colored.

The condenser now begins to receive a charge, and continues to receive it during the next quarter of a cycle, the charge attaining its maximum value when the current is of zero intensity. Hence, the *maximum charge of a condenser* in an alternating circuit is equal to the average value of the current multiplied by the time of charge, which is one-quarter of a period, that is maximum charge = average current × ¼ period. . . . .(1)

Since the time of a period = 1 ÷ frequency, the time of one-quarter of a period is ¼ × (1 ÷ frequency), or

$$\tfrac{1}{4}\text{ period} = \frac{1}{4f} \quad \text{. . . . .(2)}$$

f, being the symbol for frequency. Substituting (2) in (1)

$$\text{maximum charge} = I_{av} \times \frac{1}{4f} \quad \text{. . . . .(3)}$$

The pressure of a condenser is equal to the quotient of the charge divided by the capacity, that is

$$\text{condenser pressure} = \frac{\text{charge}}{\text{capacity}} \quad \text{. . . . .(4)}$$

Substituting (3) in (4)

$$\text{condenser pressure} = \left(I_{av} \times \frac{1}{4f}\right) \div C = \frac{I_{av}}{4fC} \quad \text{. . . . .(5)}$$

But, $I_{av} = I_{max} \times \frac{2}{\pi}$, and substituting this value of I_{av} in equation (5) gives

$$\text{condenser pressure} = \frac{I_{max} \times \frac{2}{\pi}}{4fC} = \frac{I_{max}}{2\pi fC} \quad \text{. . . . .(6)}$$

This last equation (6) represents the condenser pressure due to capacity at the point of maximum value, which pressure is opposed to the impressed pressure, that is, it is the maximum reverse pressure due to capacity.

Now, since by Ohm's law

$$I = \frac{E}{R}, \text{ or } E = I \times R$$

and as

$$\frac{I_{max}}{2\,\pi f\,C}=I_{max}\times\frac{1}{2\,\pi f\,C}$$

it follows that $\frac{1}{2\,\pi f\,C}$ is the *ohmic value* of capacity, that is, it expresses the resistance equivalent of capacity; using the symbol X_c for capacity reactance

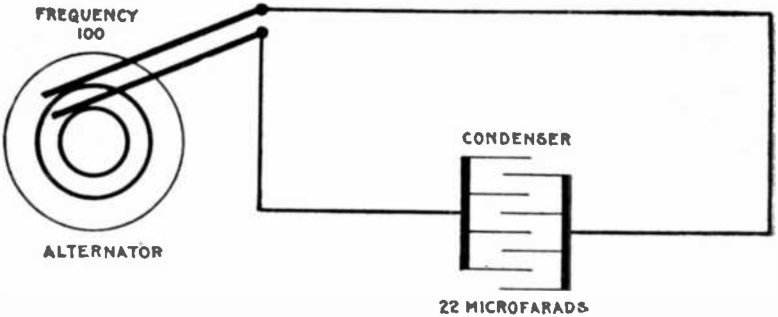


FIG. 2,035.—Diagram showing alternating circuit containing capacity. Formula for calculating the ohmic value of capacity or "capacity reactance" is $X_c = 1 \div 2\,\pi f\,C$, in which X_c = capacity reactance; $\pi = 3.1416$; f = frequency; C = capacity *in farads* (not microfarads). 22 microfarads = 22 ÷ 1,000,000 = .000022 farad. Substituting, $X_c = 1 \div (2 \times 3.1416 \times 100 \times .000022) = 72.4$ ohms.

$$X_c=\frac{1}{2\,\pi f\,C}\quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Example.—What is the resistance equivalent of a 50 microfarad condenser to an alternating current having a frequency of 100?

Substituting the given values in the expression for ohmic value

$$X_c=\frac{1}{2\,\pi f\,C}=\frac{1}{2\times 3.1416\times 100\times .000050}=\frac{1}{.031416}=31.8 \text{ ohms}.$$

If the pressure of the supply be, say 100 volts, the current would be $100 \div 31.8 = 3.14$ amperes.

Lag and Lead.—Alternating currents do not always keep in step with the alternating volts impressed upon the circuit. If there be inductance in the circuit, the current will *lag;* if there be capacity, the current will *lead* in phase. For example, fig.

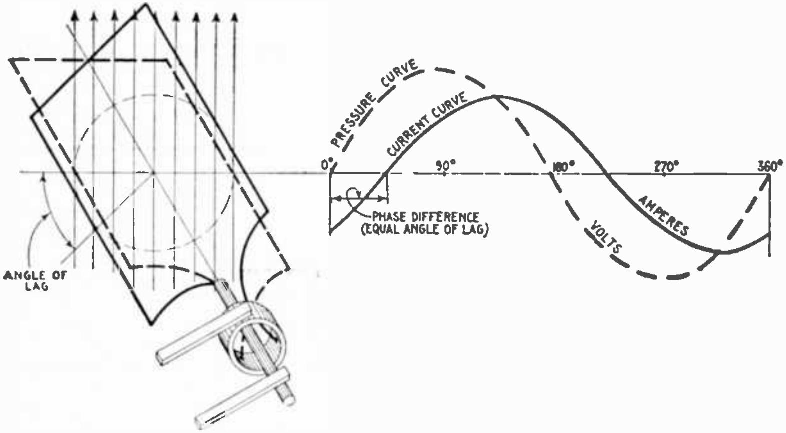


FIG. 2,036.—Pressure and current curves, illustrating *lag*. The effect of inductance in a circuit is to retard the current cycle, that is to say, if the current and pressure be in phase, the introduction of inductance will cause a phase difference, the current wave "lagging" behind the pressure wave as shown. In other words, inductance causes the current wave, indicated in the diagram by the solid curve, to lag behind the pressure wave, indicated by the dotted curve. Following the curve starting from the left end of the horizontal line, it will be noted that the current starts after the pressure starts and reverses after the pressure reverses; that is, *the current lags in phase behind the pressure,* although the frequency of both is the same.

2,036, illustrates the lag due to inductance and fig. 2,037, the lead due to capacity.

Ques. What is lag?

Ans. Lag denotes the condition where the phase of one alternating current quantity lags behind that of another.

The term is generally used in connection with the effect of inductance in causing the current to lag behind the impressed pressure.

Ques. How does inductance cause the current to lag behind the pressure?

Ans. It tends to prevent changes in the strength of the current.

When two parts of a circuit are near each other, so that one is in the

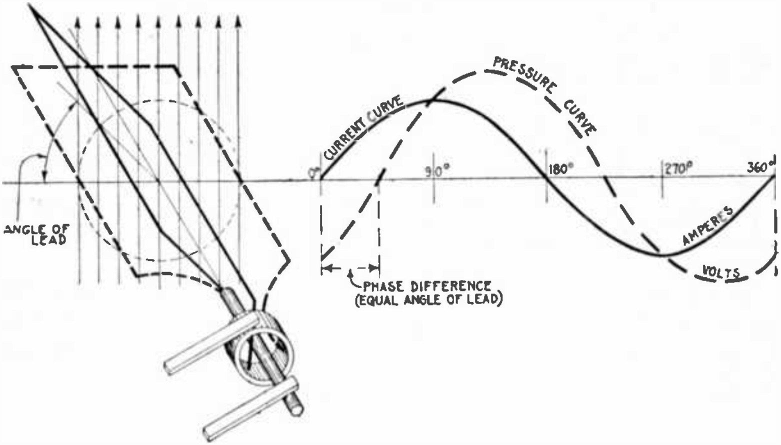


FIG. 2,037.—Pressure and current curves illustrating *lead*. The effect of capacity in a circuit is to cause the current to rise to its maximum value sooner than it would otherwise do; capacity produces an effect exactly the opposite of inductance. The phase relation between current and pressure with current leading is shown graphically by the two armature positions in full and dotted lines, corresponding respectively to current and pressure at the beginning of the cycle.

magnetic field of the other any change in the strength of the current causes a corresponding change in the magnetic field and sets up a reverse pressure in the other wire.

This induced pressure causes the current to reach its maximum value a little later than the pressure, and also tends to prevent the current diminishing in step with the pressure.

Ques. What governs the amount of lag in an alternating current?

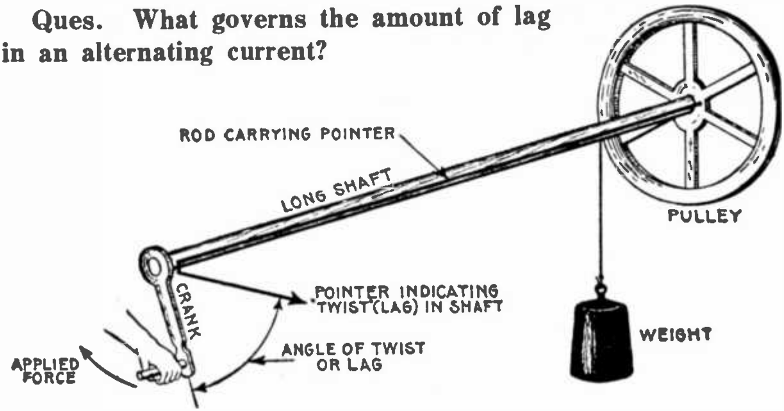


FIG. 2,038.—Mechanical analogy of lag. If at one end force be applied to turn a very long shaft, having a loaded pulley at the other end, the torsion thus produced in the shaft will cause it to twist an appreciable amount which will cause the movement of the pulley to *lag* behind that of the crank. This may be indicated by a rod attached to the pulley and terminating in a pointer at the crank end, the rod being so placed that the pointer registers with the crank when there is no torsion in the shaft. The angle made by the pointer and crank when the load is thrown on, indicates the amount of lag which is measured in degrees.

Ans. It depends on the relative values of the various pressures in the circuit, that is, upon the amount of resistance and inductance which tends to cause lag, and the amount of capacity in the circuit which tends to reduce lag and cause lead.

Ques. How is lag measured?

Ans. In degrees.

Thus, in fig. 2,036, the lag is indicated by the distance between the beginning of the pressure curve and the beginning of the current curve, and is in this case 45°.

Ques. What is the physical meaning of this?

Ans. In an actual alternator, of which fig. 2,036 is an elementary diagram showing one coil, if the current lag, say 45°

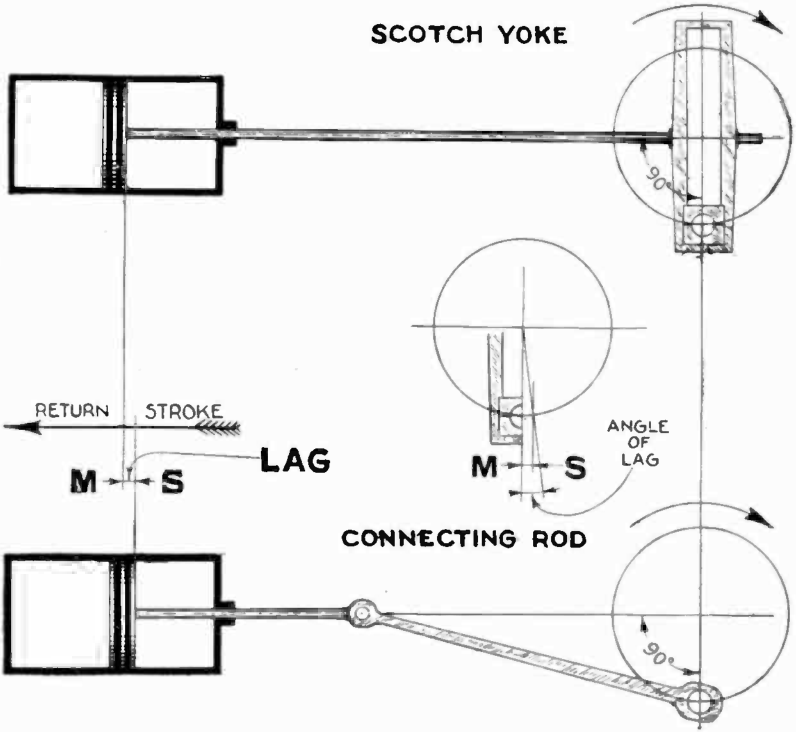


FIG., 2,039 to 2,041.—Eccentricity of the connecting rod *analogy of lag*. In a steam engine, the effect of the angularity of the connecting rod is to cause the piston to lag during the *return* stroke behind its true movement when this distortion is absent. The illustrations show the familiar Scotch yoke and connecting rod gear between piston and crank pin. The Scotch yoke gives an undistorted piston movement whereas the connecting rod introduces the distortion as plainly seen by comparing the two figures. Now with the Scotch yoke, the piston has moved the same number of divisions or "degrees" as the crank pin, whereas with the connecting rod the piston has moved a lesser number of degrees. Laying off the two angular positions of the piston in fig. 2,040, gives the *angle of lag* for the crank pin position taken in the diagrams. ***Similarly***, if there be *inductance* in an alternating current circuit, the current will *lag* behind the impressed pressure; that is, the current will rise to its maximum value later than the pressure as shown in fig. 2,036. A point to be noted is that in the analogy the lag is variable whereas in the alternating circuit it is constant for a given set of conditions.

behind the pressure, it means that the coil rotates 45° from its position of zero induction before the current starts, as in fig. 2,036.

Example 1.—A circuit through which an alternating current is passing has an inductance of 6 ohms and a resistance of 2.5 ohms. What is the angle of lag?

Substituting these values in equation (1), page 1,443,

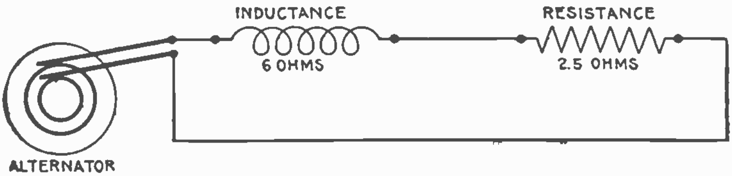


FIG. 2,042.—Diagram of circuit for example 1.

$$\tan\phi=\frac{6}{2.5}=2.4$$

Referring to the table of natural sines and tangents on page 921 the corresponding angle is approximately 67°.

Example 2.—A circuit has a resistance of 2.3 ohms and an inductance of .0034 henry. If an alternating current having a frequency of 125 pass through it, what is the angle of lag?

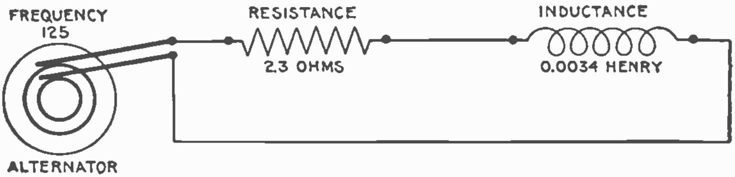


FIG. 2,043.—Diagram of circuit for example 2.

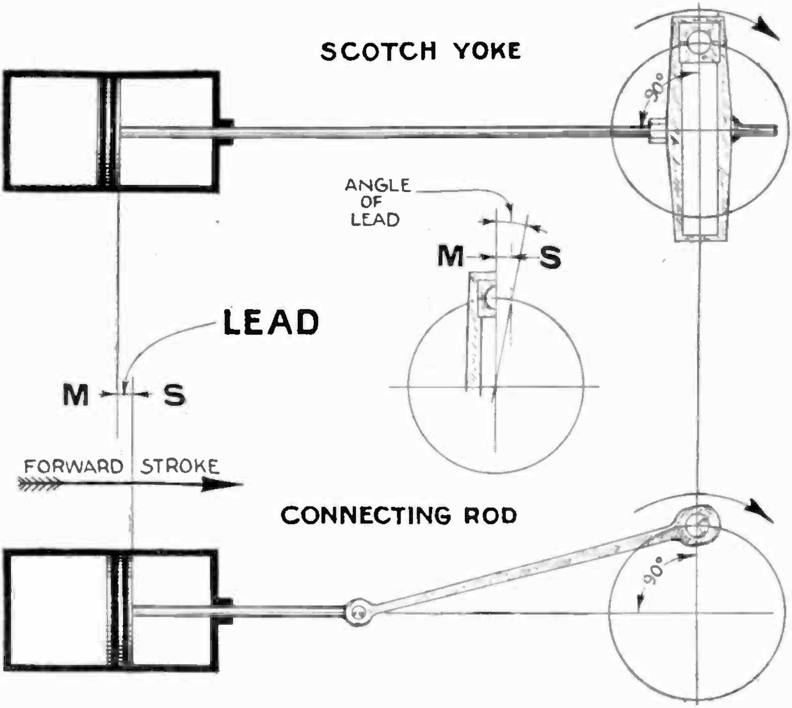
Here the inductance is given as a fraction of a henry; this must be reduced to ohms by substituting in equation (3), page 1,420, which gives the ohmic value of the inductance; accordingly, substituting the above given value in this equation

$$\text{inductance in ohms or } X_i=2\pi\times125\times.0034=2.67$$

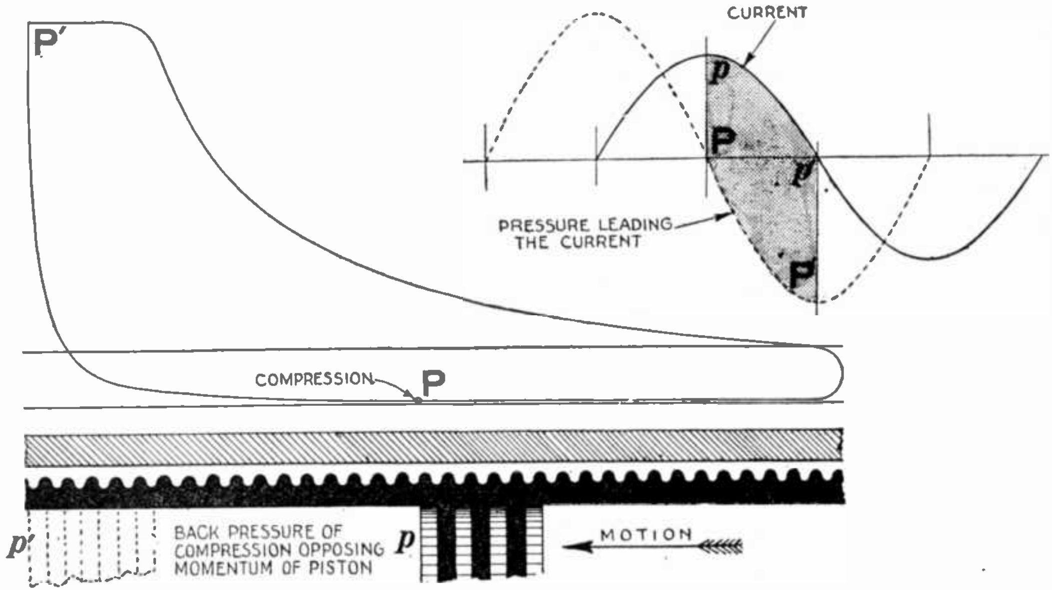
Substituting this result and the given resistance in equation (1), page 1,443,

$$\tan\phi = \frac{2.67}{2.3} = 1.16$$

the nearest angle from table (page 921) is 49°.



FIGS. 2,044 to 2,046.—Eccentricity of the connecting rod *analogy of lead*. In a steam engine, the effect of the angularity of the connecting rod is to cause the piston to travel during the forward stroke, in advance of its true movement when this distortion is absent. Now with the Scotch yoke, the piston moves the same number of divisions or "degrees" as the crank pin, as explained in figs. 2,039 to 2,041, whereas with the connecting rod the piston has moved further for the same crank pin position. ***Similarly***, if there be capacity in an alternating current circuit the current will lead or advance ahead of the impressed pressure, that is, the current will rise to its maximum value sooner than the pressure as shown in fig. 2,037.



Figs. 2,047 to 2,049.—Steam distribution analogy of lead. Those who understand indicator diagrams will easily follow this analogy which compares compression of steam (volts) in opposing the motion of the piston (amperes). In fig. 2,047 compression begins at P, and continues to P′ (corresponding to piston travel from *p* to *p′*) disregarding pre-admission. The back pressure thus set up opposes the motion of the piston and reduces its momentum to zero at the end of the stroke or position p′ corresponding to P′ thus bringing the piston to rest at that point without knock. ***Similarly,*** in the *a.c.* diagram fig. 2,048 the electric pressure reverses its direction at P and continues to P′ to oppose the motion of the current overcoming its "momentum" and reducing it to zero at position corresponding to P′. In the two diagrams the letters P and P′, and *p* and *p′* correspond in analogy to similar events.

Ques. How great may the angle of lag be?

Ans. Anything up to 90°.

The angle of lag, indicated by the Greek letter ϕ (phi), is the angle whose tangent is equal to the quotient of the inductance expressed in ohms or "spurious resistance" divided by the ohmic resistance, that is

$$\tan\phi = \frac{\text{reactance}}{\text{resistance}} = \frac{2\,\pi\, f\, L}{R} \qquad \text{(1)}$$

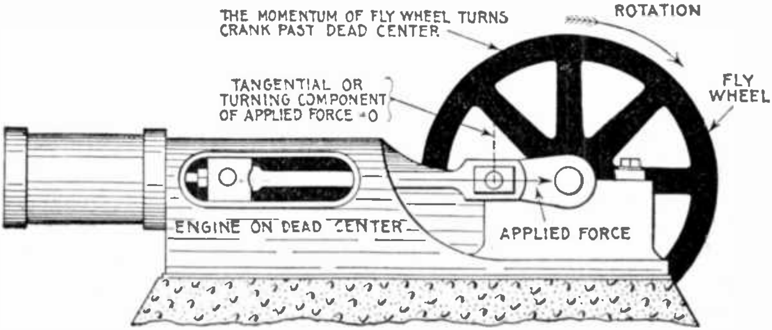


Fig. 2,050.—Steam engine analogy of current flow at zero pressure (see questions below). When the engine has reached the dead center point the full steam pressure is acting on the piston, the valve having opened an amount equal to its lead. The force applied at this instant, indicated by the arrow is perpendicular to the crank pin circle, that is, the tangential or *turning* component is equal to zero, hence there is no pressure tending to turn the crank. The latter continues in motion past the dead center because of the momentum previously acquired. Similarly, the electric current, which is here analogous to the moving crank, continues in motion, though the pressure at some instants be zero, because it acts as though it had weight, that is, it cannot be stopped or started instantly.

Ques. When an alternating current lags behind the pressure, is there not a considerable current at times when the pressure is zero?

Ans. Yes; such effect is illustrated by analogy in fig. 2,050.

Ques. What is the significance of this?

Ans. It does not mean that current could be obtained from a circuit that showed no pressure when tested with a suitable volt meter, for no current would flow under such conditions. However, in the flow of an alternating current, the pressure varies from zero to maximum values many times each second, and the instants of no pressure may be compared to the "dead centers" of an engine at which points there is no pressure to cause rotation of the crank, the crank being carried past these points by the momentum of the fly wheel. Similarly the electric current does not stop at the instant of no pressure because of the "momentum" acquired at other parts of the cycle.

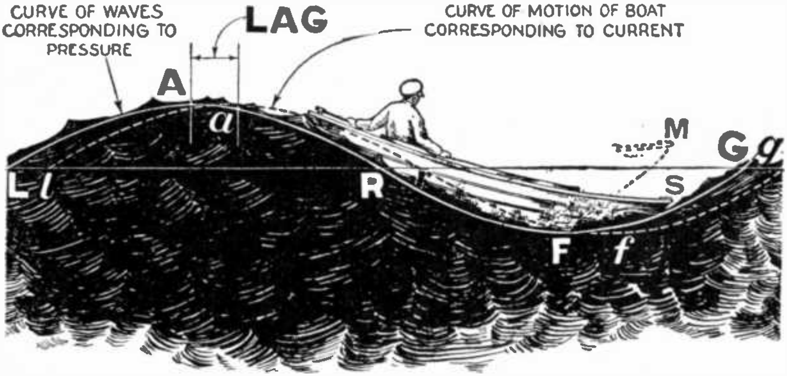


FIG. 2,051.—Marine analogy of *lag*. The view shows a fishing dory in a rough sea, LARFG, being the curve of the waves. Now if the motion of the boat were *in phase* with the waves, the same curve LARFG, would give the motion of the boat referred to a point on the water line. However, due to the inertia of the boat, its motion lags behind that of the waves, as indicated by the curve *larfg*. Thus, on the approach of a wave, as shown above, the bow of the boat submerges to such depth S, that the increased upward thrust overcomes the inertia and causes the bow to rise; this takes time and accordingly the motion of the boat *lags* behind that of the waves. *Similarly*, in an alternating current circuit, inductance causes the current to lag *behind* the pressure. M, shows normal position of dory; S, submerged or lagging position.

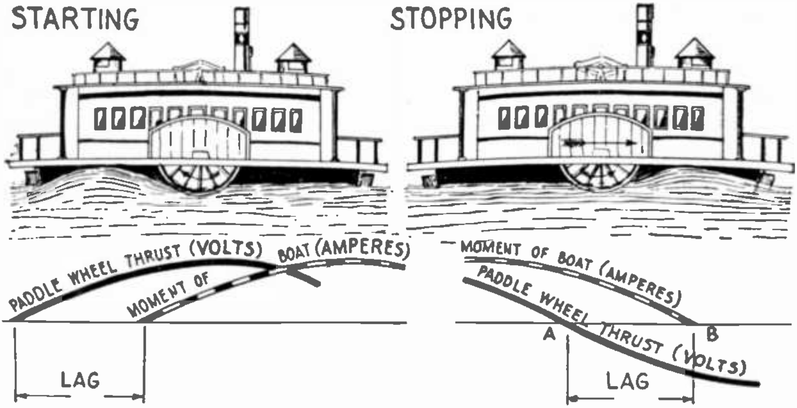
Ques. On long lines having considerable inductance, how may the lag be reduced?

Ans. By introducing capacity into the circuit.

In fact, the current may be advanced so it will be in phase with the pressure or even lead the latter, depending on the amount of capacity introduced.

There has been some objection to the term *lead* as used in describing the effect of capacity in an alternating circuit, principally on the ground that such expressions as "lead of current," "lead in phase," etc., tend to convey the idea that the effect precedes the cause, that is, the current is in advance of the pressure producing it. There can, of course, be no current until pressure has been applied, but if the circuit have capacity, it will lead the pressure, and this peculiar behavior is best illustrated by a mechanical analogy as has already been given.

Ques. What effect has lag or lead on the value of the effective current?



FIGS. 2,052 and 2,053.—Ferry boat analogy of *lag. In starting*, the paddle wheels make an appreciable thrust (*volts*) before the boat begins to move (*amperes*). Thus the movement of the boat (*amperes*) *lags* behind the thrust of the paddle wheels (*volts*). *In stopping*, the paddle wheels make several reverse turns (*reversal of a. c. volts*) before the movement of the boat (amperes) ceases, thus lagging behind the thrust of the paddles (*volts*).

Ans. As the angle of lag or lead increases, the value of the effective as compared with the virtual current diminishes.

Reactance.—The term "reactance" means simply *reaction.* It is used to express certain effects of the alternating current other than that due to the ohmic resistance of the circuit.

Thus, *inductance reactance* means the reaction due to the spurious resistance of inductance expressed in ohms; similarly, *capacity reactance*, means the reaction due to capacity, expressed in ohms.

It should be noted that the term *reactance*, alone, that is, unqualified, is generally understood to mean *inductance reactance*, though ill advisedly so.

The resistance offered by a wire to the flow of a direct current is expressed in ohms; this resistance remains constant whether the wire be straight or coiled. If an alternating current flow through the wire, there is in addition to the ordinary or "*ohmic*" resistance of the wire, a "*spurious*" resistance arising from the development of a reverse pressure due to induction, which is more or less in value according as the wire be coiled or straight. *This spurious resistance as distinguished from the ohmic resistance is called the reactance, and is expressed in ohms.*

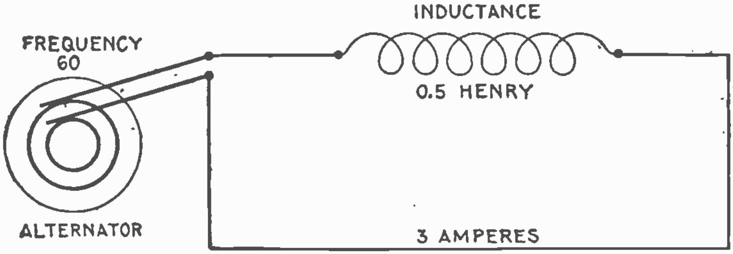


FIG. 2,054.—Diagram of the circuit for *example 1*. Here the resistance is taken at zero, but this would not be possible in practice, as all circuits contain more or less resistance though it may be, in some cases, negligibly small.

Reactance may then be defined with respect to its usual significance, that is, *inductance reactance*, as *the component of the impedance which when multiplied into the current, gives the wattless component of the pressure.*

Reactance is simply inductance measured in ohms.

Example 1.—An alternating current having a frequency of 60 is passed through a coil whose inductance is .5 henry. What is the reactance?

Here $f=60$ and $L=.5$; substituting these in formula for inductive reactance,

$$X_i=2\pi f L=2\times3.1416\times60\times.5=188.5 \text{ ohms}$$

The quantity $2\pi f L$ or reactance being of the same nature as a resistance, is used in the same way as a resistance. Accordingly, since, by Ohm's law

$$E = RI \quad \ldots\ldots (1)$$

an expression may be obtained for the volts necessary to overcome reactance by substituting in equation (1) the value of reactance previously given, thus

$$E = 2\pi f L I \quad \ldots\ldots (2)$$

Example 2.—How many volts are necessary to force a current of 3 amperes with frequency 60 through a coil whose inductance is .5 henry? Substituting in equation (2) the values here given

$$E = 2\pi f L I = 2\pi \times 60 \times .5 \times 3 = 565 \text{ volts.}$$

The foregoing example may serve to illustrate the difference in behavior of direct and alternating currents.

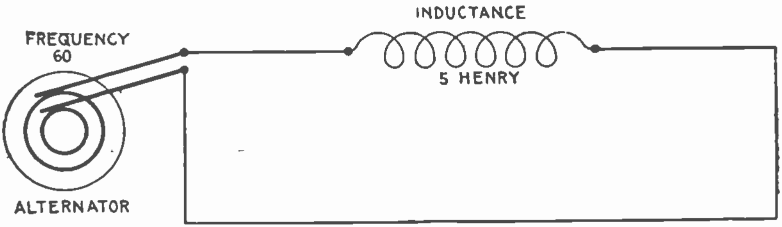


FIG. 2,055.—Diagram of circuit for *example 2.* As in *example 1,* resistance is disregarded.

As calculated, it requires 565 volts to pass only 3 amperes of alternating current through the coil on account of the considerable spurious resistance. The ohmic resistance of a coil is very small, as compared with the spurious resistance, say 2 ohms. Then by Ohm's law $I = E \div R = 565 \div 2 = 282.5$ amperes.

Instances of this effect are commonly met with in connection with transformers. Since the primary coil of a transformer has a high reactance, very little current will flow when an alternating pressure is applied. If the same transformer were placed in a direct current circuit and the current turned on it would at once burn out, as very little resistance would be offered and a large current would pass through the winding.

Example 3.—In a circuit containing only capacity, what is the reactance when current is supplied at a frequency of 100, and the capacity is 50 microfarads?

$$50 \text{ microfarads} = 50 \times \frac{1}{1,000,000} = .00005 \text{ farad}$$

capacity reactance, or

$$X_c = \frac{1}{2\pi fC} = \frac{1}{2 \times 3.1416 \times 100 \times .00005} = 31.84 \text{ ohms}$$

Impedance.—This term, strictly speaking, means the *ratio of any impressed pressure to the current which it produces in a conductor.* It may be further defined as *the total opposition in an electric circuit to the flow of an alternating current.*

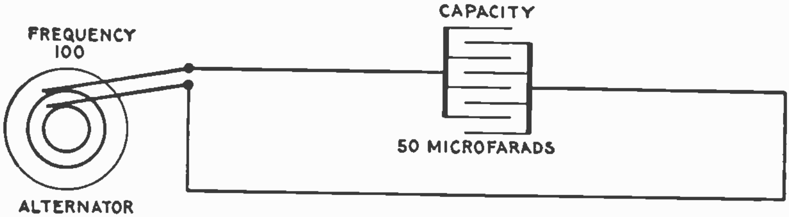


FIG. 2,056.—Diagram of circuit for *example 3.*

All power circuits for alternating current are calculated with reference to impedance. The impedance may be called the combination of:

1. Ohmic resistance;
2. Inductance reactance;
3. Capacity reactance.

The impedance of an inductive circuit which does not contain capacity is equal to *the square root of the sum of the squares of the resistance and reactance*, that is

$$impedance = \sqrt{resistance^2 + reactance^2} \quad \text{.................} (1)$$

Example 1.—If an alternating pressure of 100 volts be impressed on a coil of wire having a resistance of 6 ohms and inductance of 8 ohms, what is the impedance of the circuit and how many amperes will flow through the coil? In the example here given, 6 ohms is the resistance and 8 ohms the reactance. Substituting these in equation (1)

$$\text{Impedance} = \sqrt{6^2+8^2} = \sqrt{100} = 10 \text{ ohms}.$$

The current in amperes which will flow through the coil is, by Ohm's law using impedance in the same way as resistance.

$$\text{current} = \frac{\text{volts}}{\text{impedance}} = \frac{100 \text{ volts}}{10 \text{ ohms}} = 10 \text{ amperes}.$$

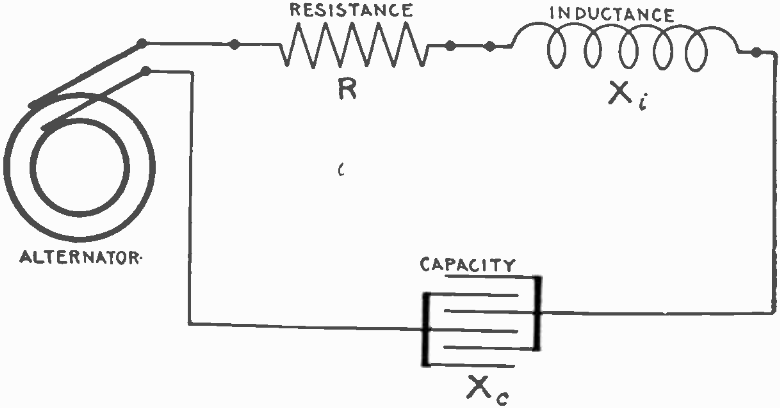


FIG. 2,057.—Diagram showing alternating circuit containing resistance, inductance, and capacity. Formula for calculating the impedance of this circuit is $Z = \sqrt{R^2+(X_i - X_c)^2}$ in which, Z = impedance; R = resistance; X_i = inductance reactance; X_c = capacity reactance. Example: What is the impedance when R = 4, X_i = 94.2, and X_c = 72.4? Substituting $Z = \sqrt{4^2+(94.2-72.4)^2} = 22.2$ ohms. Where the ohmic values of inductance and capacity are given as in this example, the calculation of impedance is very simple, but when inductance and capacity are given in milli-henrys and microfarads respectively, it is necessary to first calculate their ohmic values as in figs. 2,055 and 2,056.

The reactance is not always given but instead in some problems the frequency of the current and inductance of the circuit. An expression to fit such cases is obtained by substituting $2\pi fL$ for the reactance as follows: (using symbols for impedance and resistance)

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

Example 2.—If an alternating current, having a frequency of 60, be impressed on a coil whose inductance is .05 henry and whose resistance is 6 ohms, what is the impedance?

Here R=6; f=60, and L=.05; substituting these values in (2)

$$Z=\sqrt{6^2+(2\pi\times60\times.05)^2}=\sqrt{393}=19.8 \text{ ohms.}$$

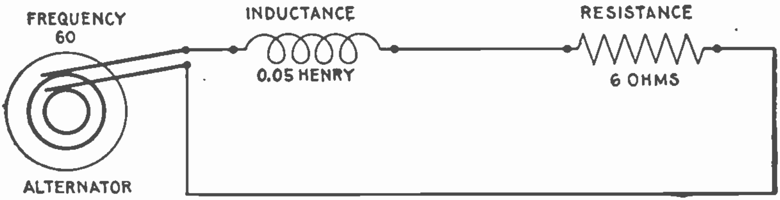


FIG. 2,058.—Diagram of circuit for *example 2.*

Example 3.—If an alternating current, having a frequency of 60, be impressed on a circuit whose inductance is .05 henry, and whose capacity reactance is 10 ohms, what is the impedance?

$$X_l=2\pi fL=2\times3.1416\times60\times.05=18.85 \text{ ohms.}$$

$$Z=X_l-X_c=18.85-10=8.85 \text{ ohms.}$$

When a circuit contains besides resistance, *both inductance*

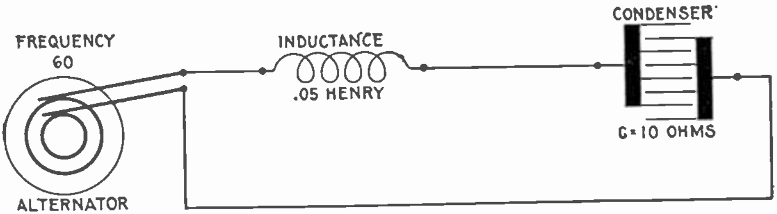


FIG. 2,059.—Diagram of circuit for *example 3.*

and capacity, the formula for impedance as given in equation (1), page 1,448, must be modified to include the reactance due to capacity, because, as explained, inductive, and capacity reactances work in opposition to each other, in the sense that the reactance of inductance acts in direct proportion to the quantity $2\pi f L$, and the reactance of capacity in inverse proportion to the quantity $2\pi f C$. The net reactance due to both, when both are in the circuit, is obtained by subtracting one from the other.

To properly estimate impedance then, in such circuits, the

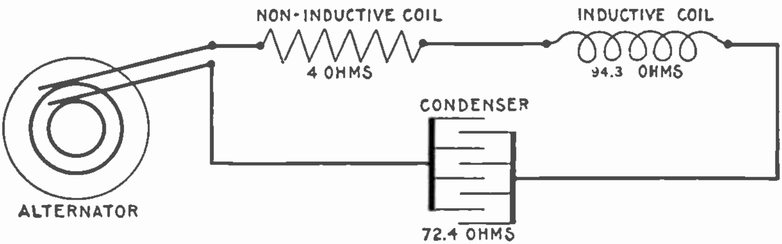


FIG. 2,060.—Diagram of circuit for *example 4.*

following equation is used:

$$\textit{impedance} = \sqrt{\textit{resistance}^2 + (\textit{inductance reactance} - \textit{capacity reactance})^2}$$

or using symbols,

$$Z = \sqrt{R^2 + (X_i - X_c)^2} \qquad (3)$$

Example 4.—A current has a frequency of 100. It passes through a circuit of 4 ohms resistance, of 150 milli-henrys inductance, and of 22 microfarads capacity. What is the impedance?

a. The ohmic resistance R, is 4 ohms.

b. The inductance reactance, or

$$X_i = 2\pi f L = 2 \times 3.1416 \times 100 \times .15 = 94.3 \text{ ohms.}$$

(note that 150 milli-henrys are reduced to .15 henry before substituting in the above equation).

c. The capacity reactance, or

$$X_c = \frac{1}{2\pi fC} = \frac{1}{2\times3.1416\times100\times.000022} = 72.4 \text{ ohms}$$

(note that 22 microfarads are reduced to .000022 farad before substituting in the formula. Why? See page 1,426.)

Substituting values as calculated in equation (3), page 1,451.

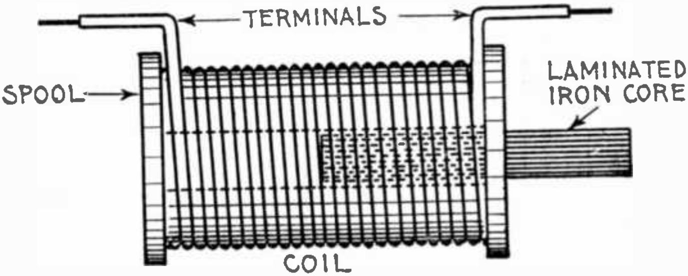


FIG. 2,061.—Simple choking coil. There is an important difference in the obstruction offered to an alternating current by ordinary resistance and by reactance. Resistance obstructs the current by dissipating its energy, which is converted into heat. Reactance obstructs the current by setting up a reverse pressure, and so reduces the current in the circuit, *without wasting much energy*, except by hysteresis in any iron magnetized. This may be regarded as one of the advantages of alternating over direct current, for, by introducing reactance into a circuit, the current may be cut down with comparatively little loss of energy. This is generally done by increasing the inductance in a circuit, by means of a device called variously a *reactance coil, impedance coil, choking coil*, or "*choker*." In the figure is a coil of thick wire provided with a laminated iron core, which may be either fixed or movable. In the first case, the inductance, and therefore also the reactance of the coil, is invariable, with a given frequency. In the second case, the inductance and consequent reactance may be respectively increased or diminished by inserting the core farther within the coil or by withdrawing it, the results of which are shown in fig. 2,062.

$$Z = \sqrt{4^2 + (94.3 - 72.4)^2} = \sqrt{495} = 22.3 \text{ ohms.}$$

Ques. Why is capacity reactance given a negative sign?

Ans. Because it reacts in opposition to inductance, that is, it tends to reduce the spurious resistance due to inductance.

In circuits having both inductance and capacity, the tangent of the angle of lag or lead as the case may be is the algebraic sum of the two reactances divided by resistance. If the sign be positive, it is an angle of lag; if negative, of lead.

Resonance.—The effects of inductance and capacity, as already explained, oppose each other. If inductance and capacity be present in a circuit in such porportion that the effect of one neutralizes that of the other, the circuit acts as though it were purely non-inductive and is said to be in a state of *resonance*.

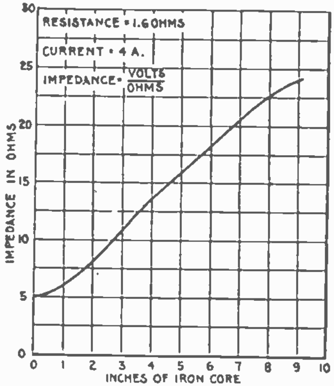


FIG. 2,062.—Impedance curve for coil with variable iron core. The impedance of an inductive coil may be increased by moving an iron wire core into the coil. In making a test of this kind, the current should be kept constant with an adjustable resistance, and volt meter readings taken, first without the iron core, and again with 1, 2, 3, 4, etc., inches of core inserted in the coil. By plotting the volt meter readings and the positions of the iron core on section paper as above, the effect of inductance is clearly shown.

For instance, in a circuit containing resistance, inductance, and capacity, if the resistance be, say, 8 ohms, the inductance 30, and the capacity 30, then the impedance is

$$\sqrt{8^2+(30^2-30^2)} = \sqrt{8^2} = 8 \text{ ohms.}$$

The formula for inductance reactance is $X_i = 2\pi f L$, and for capacity reactance, $X_c = 1 \div (2\pi f C)$; accordingly if capacity

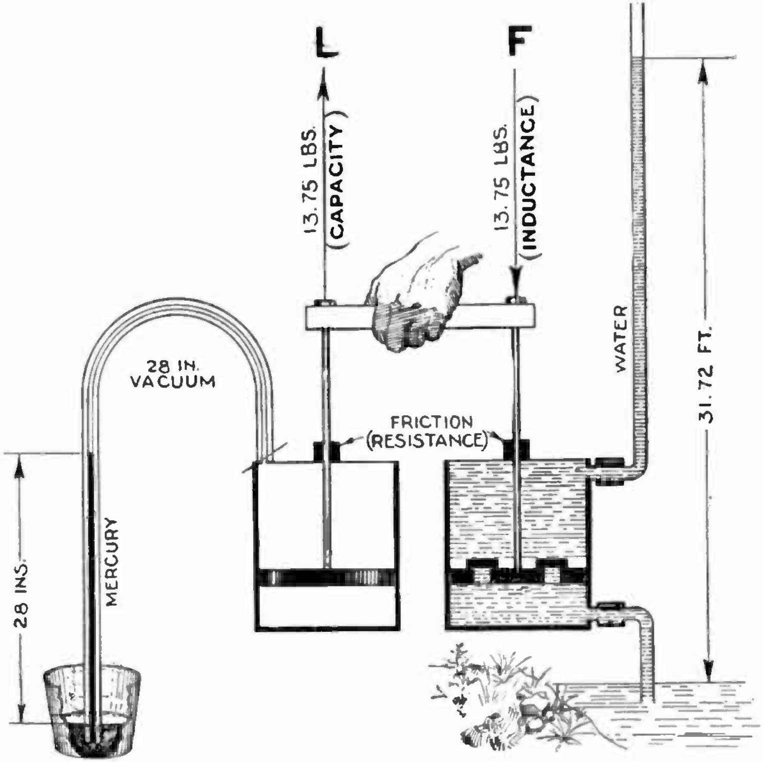


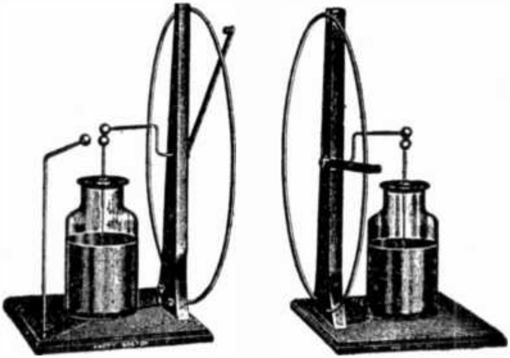
FIG. 2,063.—Mechanical analogy of *resonance*. The illustration shows an air pump and a water pump connected to a cross yoke. At the instant shown the air piston is subjected to a 28 in. vacuum, and the water piston to a pressure corresponding to a total load of 31.72 feet. These conditions produce a pressure of 13.75 lbs. acting upward on the air piston as indicated by arrow L, and an equal pressure acting downward on the water piston as indicated by the arrow F. Evidently these pressures balance each other; hence, no force is required to pull up on the yoke except that necessary to overcome any friction in the system. *Similarly*, in an alternating current circuit the effects of inductance and capacity oppose each other, and accordingly, if inductance and capacity be present in a circuit in such proportion that the effect of one neutralizes that of the other, the circuit acts as though it were purely non-inductive and is said to be in a state of resonance, that is, the only opposition to the flow of current is that due to the resistance of the circuit. In the illustration force L, corresponds to capacity; F, to inductance and the friction to resistance.

and inductance in a circuit be equal, that is, if the circuit be resonant

$$2\pi f L = \frac{1}{2\pi f C} \quad \ldots\ldots\ldots\ldots (1)$$

from which

$$f = \frac{1}{2\pi\sqrt{CL}} \quad \ldots\ldots\ldots\ldots (2)$$



FIGS. 2,064 and 2,065.—Knott separately mounted resonant Leyden jars, for demonstration of: 1, resonance between electrical circuits; 2, oscillatory character of the condenser spark; 3, tuning as applied to so-called high frequency circuits, radio experiments, etc. *In operation*, one of the jars should be charged by means of a static machine or induction coil, and at each discharge a simultaneous spark will be obtained from the other jar, providing that its loop is adjusted to the same position as the loop on the first. Changing the size of the loop on either of the jars without altering the other will throw them out of tune, and the charge on one will be much less than on the other. When in tune, the two parts of the outfit may be removed a considerable distance apart, thus showing in a very clear manner the sensitiveness of resonant circuits. The outfit is usually equipped with one quart Leyden jars, but jars either larger or smaller may be used, if at hand, thereby greatly increasing the educational value of the device, for it can be shown that to obtain resonance the value of the condenser times the inductance or loop must be the same, that is, a large jar discharging through a small part of the loop of conductor will energize the other or smaller jar through a larger part of its circuit.

Ques. What does equation (1) show?

Ans. It indicates that by varying the frequency in the proper way as by increasing or decreasing the speed of the alternator, the circuit may be made resonant, this condition being obtained when the frequency has the value indicated by equation (2).

Ques. What is the mutual effect of inductance and capacity?

Ans. One tends to neutralize the other.

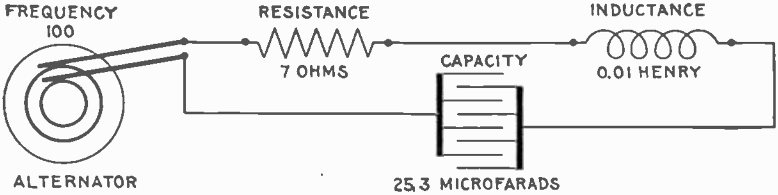


FIG. 2,066.—Diagram of a resonant circuit. A circuit is said to be resonant when the inductance and capacity are in such proportion that the one neutralizes the other, the circuit then acting as though it contained only resistance. In the above circuit $X_i = 2\pi f L = 2 \times 3.1416 \times 100 \times .01 = 6.28$ ohms; $X_c = 1 \div (2 \times 3.1416 \times 100 \times .000253) = 6.28$ ohms whence the resultant reactance $= X_i - X_c = 6.28 - 6.28 = 0$ ohms. $Z = \sqrt{R^2 + (X_i - X_c)^2} = \sqrt{7^2 + 0^2} =$ 7 ohms.

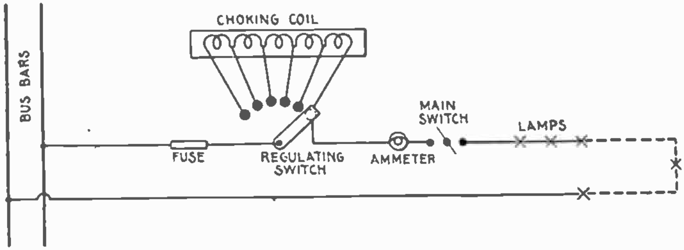


FIG. 2,067.—Application of a choking coil to a lighting circuit. The coil is divided into sections with leads running to contacts similar to a rheostat. Each lamp is provided with an automatic short-circuiting cutout, and should one, two, or more of them fail, a corresponding number of sections of the choking apparatus is put in circuit to take the place of the broken lamp or lamps, and thus keep the current constant. It must not be supposed that this arrangement of lamps, etc., is a general one; it being adopted to suit certain special conditions.

Ques. What effect has resonance on the current?

Ans. It brings the current in phase with the impressed pressure.

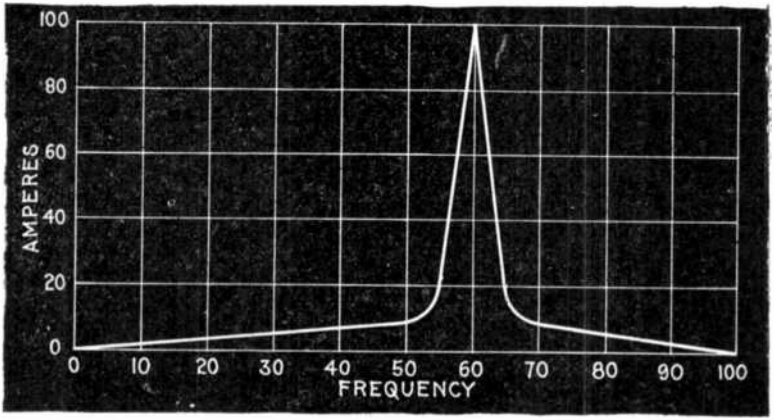


FIG. 2,068.—Curve showing variation of current by increasing the frequency in a circuit having inductance and capacity. The curve serves to illustrate the "critical frequency" or frequency producing the maximum current. The curve is obtained by plotting current values corresponding to different frequencies, the pressure being kept constant.

It is very seldom that a circuit is thus balanced unless intentionally brought about; when this condition exists, the effect is very marked, the pressure rising excessively and bringing great strain upon the insulation of the circuit.

Ques. Define "critical frequency."

Ans. In bringing a circuit to a state of resonance by increasing the frequency, the current will increase with increasing frequency until the critical frequency is reached, and then the current will decrease in value for further increase of frequency. The critical frequency occurs when the circuit reaches the condition of resonance.

Ques. How is the value of the current at the critical frequency determined?

Ans. By the resistance of the circuit.

Skin Effect.—This is the tendency of alternating currents to avoid the central portions of solid conductors and to flow or pass mostly through the outer portions. The so called skin effect becomes more pronounced as the frequency is increased.

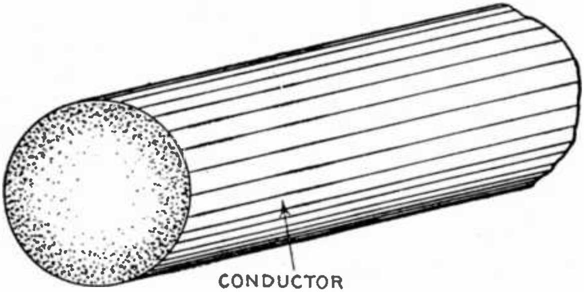


FIG. 2,069.—Section of conductor illustrating "skin effect" or tendency of the alternating current to distribute itself unequally through the cross section of the conductor as shown by the varied shading flowing most strongly in the outer portions of the conductor. For this reason it has been proposed to use hollow or flat conductors instead of solid round wires. However with frequency not exceeding 100 the skin effect is negligibly small in copper conductors of the sizes usually employed. Where the conductor is large or the frequency high the effect may be judged by the following examples calculated by Professor J. J. Thomson: In the case of a copper conductor exposed to an electromotive force making 100 periods per second at 1 centimeter from the surface, the maximum current would be only .208 times that at the surface; at a depth of 2 centimeters it would be only .043; and at a depth of 4 centimeters less than .002 part of the value at the surface. If the frequency be a million per second the current at a depth of 1 millimeter is less than one six-millionth part of its surface value. The case of an iron conductor is even more remarkable. Taking the permeability at 100 and the frequency at 100 per second the current at a depth of 1 millimeter is only .13 times the surface value; while at a depth of 5 millimeters it is lese than one twenty-thousandth part of its surface value. The disturbance of current density may be looked upon as a self-induced eddy current in the conductor. It necessarily results in an increase of ohmic loss; as compared with a steady current: proportional to the square of the total current flowing and consequently gives rise to an apparent increase of ohmic resistance. The coefficient of increase of resistance depends upon the dimensions and the shape of the cross section, the frequency and the specific resistance. A similar but distinct effect is experienced in conductors due to the neighborhood of similar parallel currents. For example, in a heavy multicore cable the non-uniformity of current density in any core may be considered as partly due to eddy currents induced by the currents in the neighboring cores and partly to the self-induced eddy current. It is only the latter effect which should rightly be considered as comprised under the term *skin effect*.

Ques. What is the explanation of skin effect?

Ans. It is due to eddy currents induced in the conductor.

Consider the wire as being composed of several small insulated wires placed closely together. Now when a current is started along these separate wires, mutual induction will take place between them, giving rise to momentary reverse pressures. Those wires which are nearer the center, since they are completely surrounded by neighboring wires, will clearly have stronger reverse pressures set up in them than those on or near the outer surface, so that the current will meet less opposition near the surface than at the center, and consequently the flow will be greater in the outer portions.

Ques. What is the result of skin effect?

Ans. It results in an apparent increase of resistance.

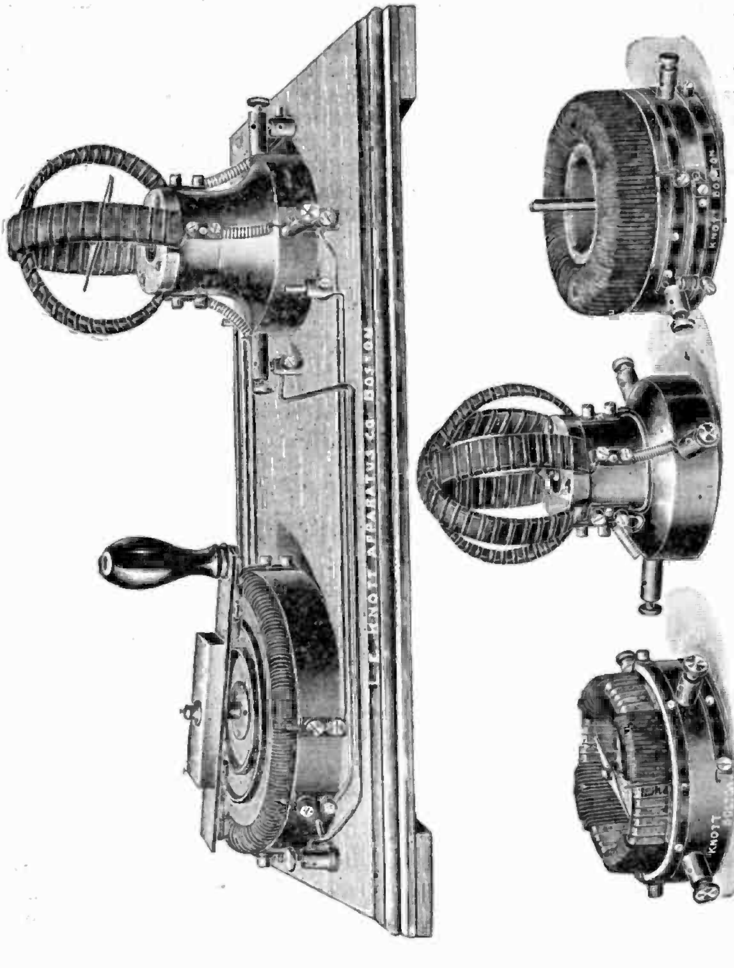
The coefficient of increase of resistance depends upon the dimensions and the shape of the cross section, the frequency, and the specific resistance.

Hughes, about 1883, called attention to the fact that the resistance of an iron telegraph wire was greater for rapid periodic currents than for steady currents.

In 1888 Kelvin showed that when alternating currents at moderately high frequency flow through massive conductors, the current is practically confined to the skin, the interior portions being largely useless for the purpose of conduction. The mathematical theory of the subject has been developed by Kelvin, Heaviside, Rayleigh, and others.

TEST QUESTIONS

1. *Define alternating currents.*
2. *What are the advantages and disadvantages of alternating currents?*
3. *State alternating current principles.*
4. *What is the application of the sine curve?*
5. *What is the meaning of the equation $y=\sin\phi$?*
6. *What is an alternation?*



FIGS. 2,070 to 2,073.—Knott alternating current demonstration apparatus. This outfit affords a convenient and practical manner of demonstrating a wide range of alternating and three phase current experiments. *In use*, two to six volts of battery

7. *What is the amplitude of the current?*
8. *Define the terms period and frequency.*
9. *What frequencies are used in commercial machines?*
10. *What is the advantage of low frequency?*
11. *What is phase?*
12. *Explain the terms in phase and out of phase.*
13. *What is synchronism?*
14. *What is the difference between maximum, average and virtual volts?*
15. *What are effective volts and amperes?*
16. *What is the expression for form factor and what does it indicate?*
17. *What is the relation between the shape of the wave curve and the form factor?*
18. *What determines the form of the wave?*
19. *What is single phase current?*
20. *Describe two phase and three phase current.*
21. *Give hydraulic analogy illustrating the difference between direct (continuous) and alternating current.*
22. *How must an alternator be constructed to generate two phase current?*
23. *How many wires are required for two phase and three phase distribution?*
24. *How is three phase current generated?*
25. *What is induction?*
26. *Describe an experiment illustrating self induction in an alternating current circuit.*

FIGS. 2,070 to 2,073.—*Text continued.* current should be used. This current is transformed into alternating or three phase current by the distributing apparatus, fig. 2,070. This current will flow through the Ferraris coils or the four or six coil iron ring, whichever happens to be in connection, as in fig. 2,070 The magnetic needle or the iron disc inside within the coils of the Ferraris coils will rotate under the influence of the rotating field. Synchronous rotation can be obtained by using the four or six coil iron rings (Tesla ring) indicated by the magnetic needle or iron disc. The asynchronous rotation can be demonstrated by inserting the squirrel cage rotor in place of the magnetic needle or the iron disc. The rings of the Ferraris coil are wound with wires of different colors; the coils of the iron rings have also wires of different colors. Fig. 2,070, current distributing apparatus; fig. 2,071, four coil iron ring; fig. 2,072, Ferraris triple coil, fig. 2,073, six coil iron ring.

27. *What is the difference between ohmic and spurious resistance?*
28. *What is the unit of induction?*
29. *What other name is given to the henry?*
30. *What is the formula for the henry?*
31. *Give hydraulic and mechanical analogy of induction.*
32. *Describe a choke coil.*
33. *What is the ohmic value of inductance?*
34. *Define capacity.*
35. *Give hydraulic analogy illustrating capacity.*
36. *What is the effect of capacity?*
37. *Name the unit of capacity and define it.*
38. *Explain the effect of a condenser in direct and alternating current circuits.*
39. *What is specific inductive capacity?*
40. *How are capacity tests usually made?*
41. *What is the ohmic value of capacity?*
42. *What is the difference between lag and lead? Define each.*
43. *How does inductance cause the current to lag behind the pressure?*
44. *How is lag measured?*
45. *Give analogies of lag and lead.*
46. *How great may the angle of lag be?*
47. *Can there be current flow at zero pressure?*
48. *Define reactance.*
49. *What is impedance?*
50. *What is resonance?*
51. *Give mechanical analogy of resonance.*
52. *What is the mutual effect of inductance and capacity?*
53. *Explain the terms critical frequency and skin effect.*

CHAPTER 48

Alternating Current Diagrams

Whenever an alternating pressure is impressed on a circuit, *part of it is spent in overcoming the resistance, and the rest goes to balance the reverse pressure due to self-induction.*

The total pressure applied to the circuit is known as the *impressed pressure*, as distinguished from that portion of it called the *active pressure* which is used to overcome the resistance, and that portion called the *self-induction pressure* used to balance the reverse pressure of self-induction.
The intensity of the reverse pressure induced in a circuit due to self-induction is proportional to the *rate of change in the current strength.*

Thus a current, changing at the rate of one ampere per second, in flowing through a coil having a coefficient of self-induction of one henry, will induce a reverse pressure of one volt.

Ques. Describe how the rate of change in current strength varies, and how this affects the reverse pressure.

Ans. The alternating current varies from zero to maximum strength in one-quarter period, that is, in one-quarter revolution or 90° of the generating loop as represented by the sine curve in fig. 2,074. Now, during, say, the first 10 degrees of rotation (from 0 to A), the current jumps from zero value to A′, or 4¼ amperes, according to the scale; during some intermediate 10 degrees of the quarter revolution, as from B to C, the current increases from B′ to C′ or 2⅞ amperes, and during another 10 degrees as from D to E, at the end of one-quarter revolution where the sine curve reaches its amplitude, it rises and falls ⅓ ampere. It is thus seen that the *rate of change* varies from a maximum when the current is least, to zero when the current

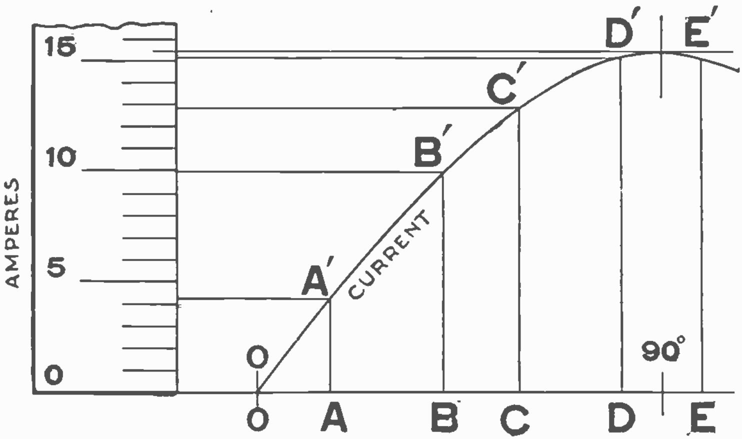


FIG. 2,074.—Sine curve showing that the *rate of change* in the strength of an alternating current is *greatest when the current is least, and zero when the current is at a maximum.* This is evident from the diagram, since during say the first 10° as OA, the current increases 4¼ amperes; during BC, 2⅞ amperes; during DE, it rises and falls ⅓ ampere. The reverse pressure of self-induction being proportional to the *rate of change* of the current, is a maximum when the current is zero, and zero when the current is a maximum, *giving a phase difference of 90° between reverse pressure of self-induction and current.*

is at its maximum. Accordingly, the reverse pressure of self-induction *being proportional to the rate of change in the current strength,* is greatest when the current is at zero value, and zero when the current is at its maximum.

This relation is shown by curves in fig. 2,075, and it should be noted that *the reverse pressure and current are 90° apart* in phase. For this reason many alternating current problems may be solved graphically by the use of right angle triangles, the sides, drawn to some arbitrary scale, to represent the quantities involved, such as resistance, reactance, impedance, etc.

Properties of Right Angle Triangles.—In order to understand the graphical method of solving alternating current problems, it is necessary to know why certain relations exist between the sides of a right angle triangle. For instance, in every right angle triangle:

The square of the hypothenuse is equal to the sum of the squares of the other two sides.

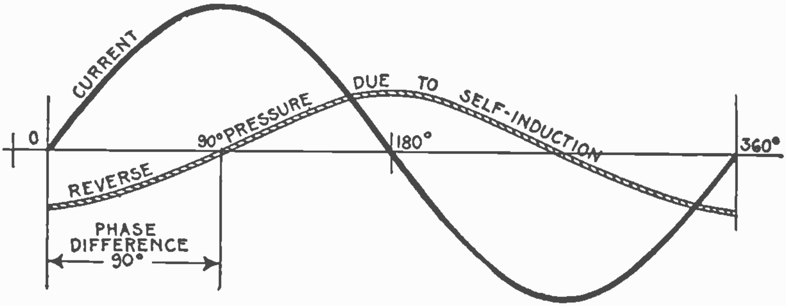


FIG. 2,075.—Sine curves showing phase relation between current and reverse pressure of self-induction. This reverse pressure, *being proportional to the rate of change in the current strength, is greatest when the current is at zero value, and zero when the current is maximum*, and in phase is 90° behind the current.

That is, condensing this statement into the form of an equation:

$$hypothenuse^2 = base^2 + altitude^2 \ldots\ldots\ldots\ldots (1)$$

the horizontal side being called the base and the vertical side, the altitude.

This may be called the equation of the right angle triangle.

Ques. Why is the square of the hypothenuse of a right

angle triangle equal to the sum of the squares of the other two sides?

Ans. This may be explained with the aid of fig. 2,076.

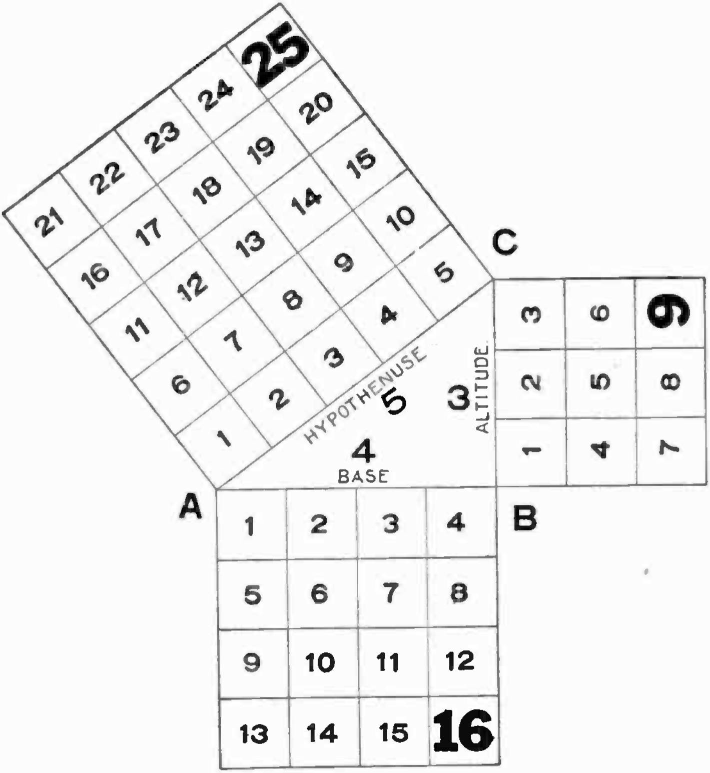


FIG. 2,076.—*In a right angle triangle the square on the hypothenuse is equal to the sum of the squares on the other two sides.* That is: *hypothenuse*^{2} = *base*^{2} + *altitude*^{2}. Draw AB, 4 inches long, and BC, 3 inches long and at right angles to AB. Join AC, which will be found to be 5 inches long. From the diagram, it must be clear that the square on AC = sum of squares on AB and BC; that is, $5^2 = 4^2 + 3^2$. Further, $4^2 = 5^2 - 3^2$; $3^2 = 5^2 - 4^2$; $5 = \sqrt{4^2+3^2}$; $4 = \sqrt{5^2-3^2}$; $3 = \sqrt{5^2-4^2}$.

Draw a line AB, 4 inches in length and erect a perpendicular BC, 3 inches in height; connect A and C, giving the right angle triangle ABC. It will be found that AC, the hypothenuse of this triangle is 5 inches long. If squares be constructed on all three sides of the triangle, the square on the hypothenuse will have an area of 25 sq. ins.; the square on the base, 16 sq. ins., and the square on the altitude, 9 sq. ins. Then from the figure $5^2 = 4^2 + 3^2$, that is $25 = 16 + 9$.

Repeating equation (1). it is evident from the figure that

$$\left.\begin{matrix} hypothenuse^2 \\ 5^2 \end{matrix}\right\} = \left\{\begin{matrix} base^2 + altitude^2 \\ 4^2 \quad\quad 3^2 \end{matrix}\right\}$$

that is,

$$25 = 16 + 9.$$

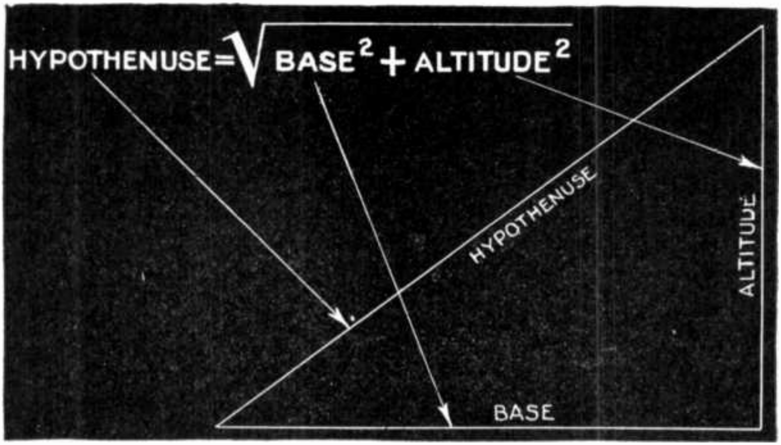


FIG. 2,077.—Graphical *representation of the* formula: *hypothenuse* $= \sqrt{\text{base}^2 + \text{altitude}^2}$.

In the right angle triangle, the following relations also hold:

$$base^2 = hypothenuse^2 - altitude^2 \ldots\ldots\ldots\ldots (2)$$

$$4^2 = 5^2 - 3^2$$

$$altitude^2 = hypothenuse^2 - base^2 \ldots\ldots\ldots\ldots (3)$$

$$3^2 = 5^2 - 4^2$$

In working impedance problems, it is not the square of any of the quantities which the sides of the triangle are used to represent that is required, but the quantities themselves, that is, the sides. Hence extracting the square root in equations (1), (2) and (3), the following are obtained:

$$hypothenuse = \sqrt{base^2 + altitude^2} \qquad (4)$$

$$5 = \sqrt{4^2 + 3^2}$$

$$base = \sqrt{hypothenuse^2 - altitude^2} \qquad (5)$$

$$4 = \sqrt{5^2 - 3^2}$$

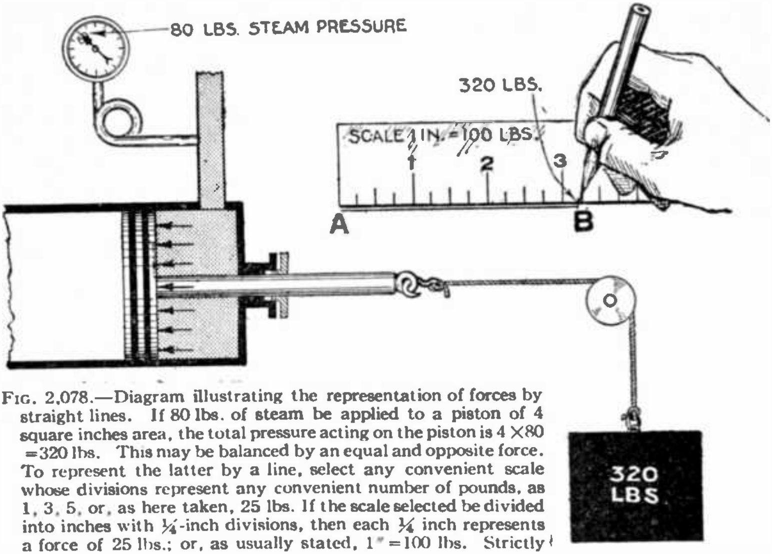


FIG. 2,078.—Diagram illustrating the representation of forces by straight lines. If 80 lbs. of steam be applied to a piston of 4 square inches area, the total pressure acting on the piston is 4 × 80 = 320 lbs. This may be balanced by an equal and opposite force. To represent the latter by a line, select any convenient scale whose divisions represent any convenient number of pounds, as 1, 3, 5, or, as here taken, 25 lbs. If the scale selected be divided into inches with ¼-inch divisions, then each ¼ inch represents a force of 25 lbs.; or, as usually stated, 1″ = 100 lbs. Strictly speaking 1″ is equivalent to 100 lbs. Draw the line **A B** = 3.2 then its length represents the magnitude of the force or 320lbs., that is, 3.2 × 100 = 320 lbs.

$$altitude = \sqrt{hypothenuse^2 - base^2} \qquad (6)$$

$$3 = \sqrt{5^2 - 4^2}$$

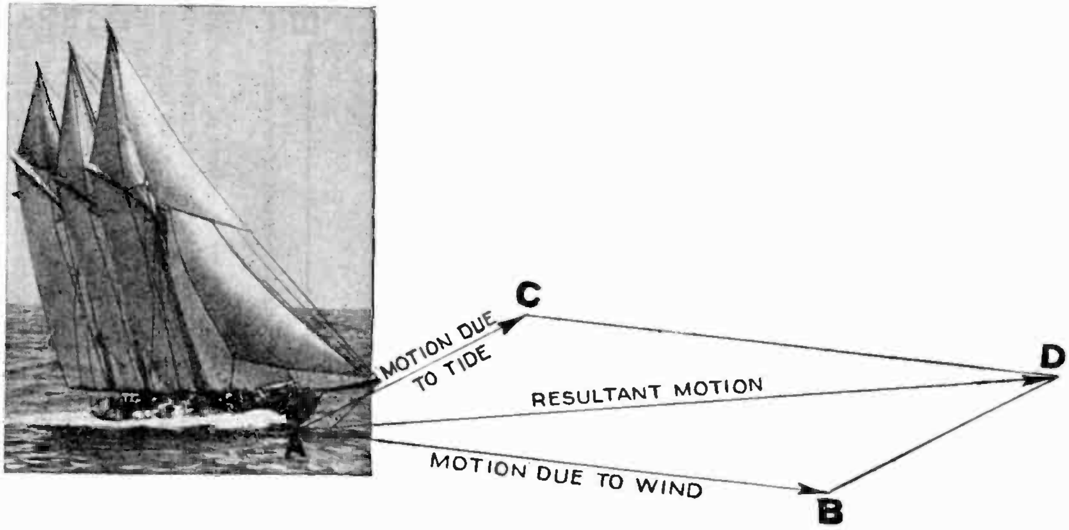


FIG. 2,079.—Parallelogram of forces for boat acted upon by both wind and tide.

Representation of Forces by Lines.—A single force may be represented in a drawing by a straight line. In the representation of forces:

1. The point of application of the force is indicated by an extremity of the line.
2. The intensity of the force by the length of the line.
3. The direction of the force by the direction of the line, an arrow head being placed at an extremity defining the direction.

Thus in fig. 2,078, the force necessary to balance the thrust on the steam piston may be represented by the straight line AB, whose length measured on any convenient scale represents the intensity of the force, and whose direction represents the direction of the force.

Composition of Forces.—This is the operation of finding a *single force whose effect is the same as the combined effect of two or more given forces.* The required force is called the *resultant* of the given forces.

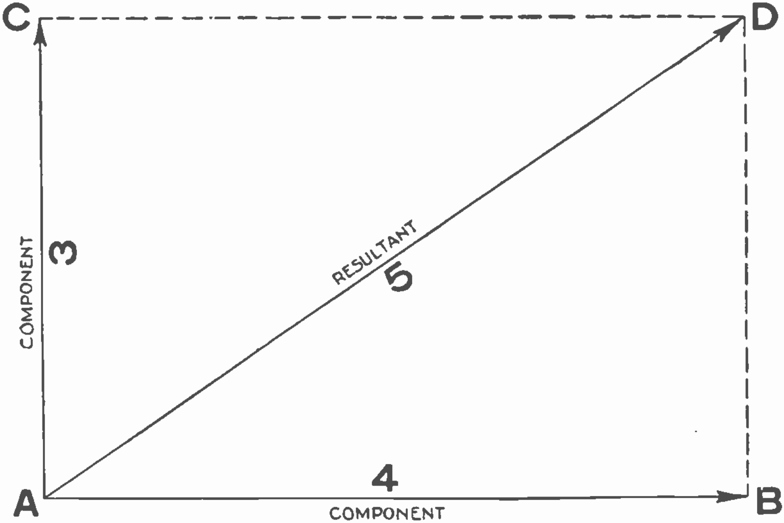


FIG. 2,080.—Parallelogram of forces; method of obtaining the resultant of two components acting at right angles.

The composition of forces may be illustrated by the effect of the wind and tide on a schooner as in fig. 2,079. Supposing the boat be acted upon by the wind so that in a given time, say half an hour, it would be moved in the direction and a distance represented by the line AB, and that in the same time the tide would carry it from A, to C. Now, lay down AB, to any convenient scale, representing the effect of the wind, and AC, that of the tide, and draw BD, equal, and parallel to AC, and CD, equal and parallel to AB, then the diagonal AD, will represent the direction and distance the boat will move under the combined effect of wind and tide.

Ques. In fig. 2,079 what is the line AD called?

Ans. The *resultant*, that is, it represents the actual movement of the boat resulting from the combined forces of wind and tide.

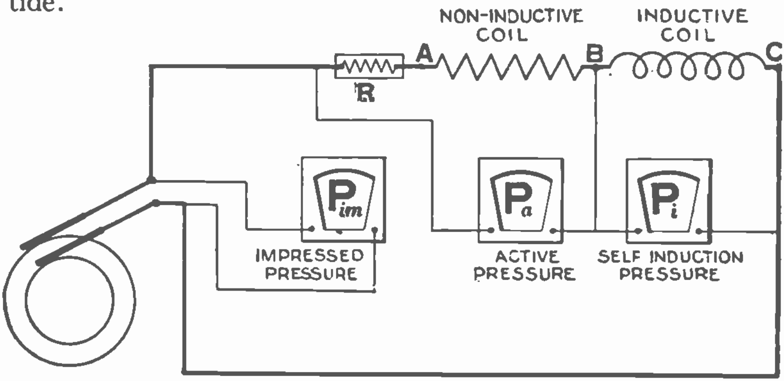


FIG. 2,081.—Diagram illustrating the *active*, and *self-induction* pressures, or the two components of the impressed pressure in circuits containing resistance and inductance. The active pressure is the volts required to overcome the resistance of the circuit. In the figure only the portion from A to C, is considered as having resistance (the rest being negligibly small) except at R, a resistance equivalent to that of the inductive coil is inserted next to the non-inductive coil, so Pa will give the total "ohmic drop" or active pressure, that is, the pressure necessary to force any equivalent direct current from A to C. This active pressure Pa or component of the impressed pressure is in phase with the current. The other component or self-induction pressure Pi that is the reactance drop necessary to overcome the reverse pressure of self-induction and is at right angles to the current and 90° ahead of the current in phase. It is registered by a volt meter between B and C, less the pressure due to ohmic resistance of the inductive coil. The impressed pressure Pim then or total pressure required to force electricity around the circuit *not including the resistance* R (which is removed from the circuit when the reading of the impressed pressure is taken), is equal to the square root of the sum of the squares of the two components, that is, $Pim = \sqrt{(Pa)^2 + (Pi)^2}$.

Ques. What are the forces, AB and AC in fig. 2,079, represented by the sides of the parallelogram, and which act upon a body to produce the resultant, called?

Ans. The *components*.

Example.—Two forces, one of 3 lbs. and one of 4 lbs. act at a point A, in a body and at right angles, what is the resultant?

Take any convenient scale, say 1 in. = 1 lb., and lay off (fig. 2,080). AB = 4 ins. = 4 lbs.; also, AC (at right angles to AB) = 3 ins. = 3 lbs. Draw CD and BD, parallel to AB and AC, respectively, and join AD. The line AD, is the resultant of the components AB and AC, and when measured on the same scale from which AB and AC, were drawn will be found to be 5 inches long, which represents 5 lbs. acting in the direction AD.

Circuits Containing Resistance and Inductance.—In circuits of this kind where the impressed pressure encounters both re-

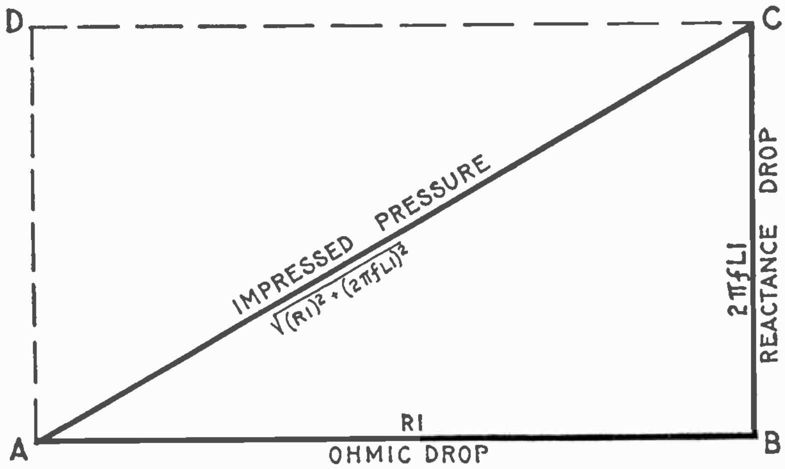


FIG. 2,082.—Graphical method of obtaining the impressed pressure in circuits containing resistance and inductance, having given the ohmic drop, and reactance drop due to inductance. With any convenient scale lay off AB = ohmic drop and erect the perpendicular BC = reactance drop (using same scale). Join AC, whose length (measured with same scale) will give the impressed pressure. Constructing a parallelogram with dotted lines AD and CD, it is evident that AC, is the *resultant* of the two *components* AB, and BC, or its equal AD.

sistance and inductance, it may be looked upon as split up into two components, as already explained, one of which is necessary to overcome the resistance, and the other, the inductance. That is, the impressed pressure is split up into

1. *Active pressure*, to overcome resistance;

2. *Self-induction pressure*, to overcome inductance.

The active pressure is *in phase with the current.*

The self induction pressure is *at right angles to the current and 90 degrees ahead of the current in phase.*

Ques. Why is the active pressure in phase with the current?

Ans. The pressure used in overcoming resistance is from Ohm's law, E = RI. Hence, when the current is zero, E, is zero, and when the current is a maximum E, is a maximum. Hence, that component of the impressed pressure necessary to overcome the resistance must be *in phase with the current.*

Ques. Why is this?

Ans. Since the *reverse pressure of self induction* is 90° behind the current, the component of the impressed pressure necessary to overcome the reverse pressure of self-induction, being opposite to this, will be represented as being 90° ahead of the current.

The distinction between the reverse pressure of self-induction, that is, the induced pressure, and the pressure necessary to overcome self-induction should be carefully noted. They are two equal and opposite forces, that is, two balancing forces just as it is shown in fig. 2,078. Here, in analogy, the thrust of the piston may represent the induced pressure and the equal and opposite force indicated by the line AB, the component of the impressed pressure necessary to balance the induced pressure.

The Active Pressure or "Ohmic Drop."—The component of the impressed pressure necessary to overcome resistance, is from Ohm's law:

$$active\ pressure = ohmic\ resistance \times virtual\ current$$

that is

$$\mathbf{E_a = R_o I_v} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

this is the "ohmic drop" and may be represented by a line AB, fig. 2,082 drawn to any convenient scale, as for instance, 1 in. = 10 volts.

The Self-Induction Pressure or "Reactance Drop."—The component of the impressed pressure necessary to overcome the induced pressure, is from Ohm's law:

inductance pressure = inductance reactance × virtual current;

that is,

$$E_i = X_i I_v \text{.......................... (2)}$$

Now the reactance X_i, that is the spurious resistance, is obtained from the formula

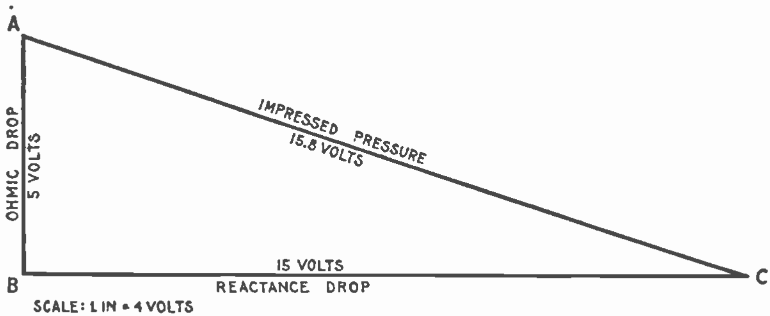


FIG. 2,083.—Diagram for impressed pressure on circuit containing 5 volts ohmic drop and 15 volts reactance drop.

$$X_i = 2\pi f L \text{ .... (3)}$$

as explained on page 1,420, and in order to obtain the volts necessary to overcome this spurious resistance, that is, the "reactance drop" as it is called, the value of X_i in equation (3) must be substituted in equation(2), giving

$$E_i = 2\pi f LI \text{.................... (4)}$$

writing simply I for the virtual pressure.

Since the pressure impressed on a circuit is considered as made up of two components, one in phase with the current and one at right angles to the current, the component E_i or "reactance drop" as given in equation (4) may be represented by the line BC, in fig. 2,082, at right angles to AB, and of a length BC, measured with the same scale as was measured AB, to correspond to the value indicated by equation (4).

Example.—In an alternating circuit, having an ohmic drop of 5 volts, and a reactance drop of 15 volts, what is the impressed pressure?

With a scale of say, ¼ inch = one volt, lay off, in fig. 2,083. AB = 5 volts = 1¼ in., and, at right angles to it, BC = 15 volts = $\frac{15}{4}$ or 3¾ ins. Join AC; this measures 3.95 inches, which is equivalent to 3.95×4 = 15.8 volts, the impressed pressure. By using good paper, such as bristol board, a 6H pencil, engineers' scale and triangles or square, such problems are solved with precision. By calculation impressed pressure = $\sqrt{5^2+15^2}$ = 15.8 volts. Note that the diagram is drawn with the side BC horizontal instead of AB, simply to save space.

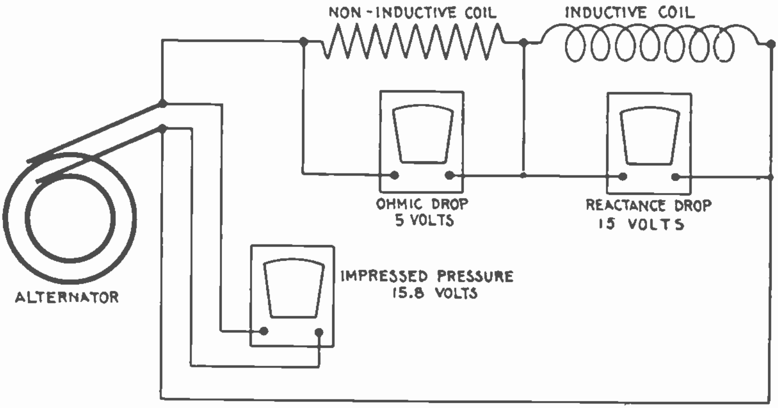


FIG. 2,084.—Diagram of circuit containing 5 volts ohmic drop, and 15 volts reactance drop.

Example 1.—In an alternating circuit, having an ohmic drop of 5 volts and an impressed pressure of 15.8 volts, what is the reactance drop?

In fig. 2,085, draw a horizontal line of indefinite length and at any point B erect a perpendicular AB = 5 volts. With A as center and radius of length equivalent to 15.8 volts, describe an arc cutting the horizontal line at C. This gives BC, the reactance drop required, which by measurement is 15 volts.

Example 2.—An alternating current of 10 amperes having a frequency of 60, is impressed on a circuit containing a resistance of 5 ohms and an inductance of 15 milli-henrys. What is the impressed pressure?

The active pressure or ohmic drop is 5×10 = 50 volts.

The inductance reactance or X_i is $2 \times 3.1416 \times 60 \times .015 = 5.66$ ohms. Substituting this and the current value 10 amperes in the formula for inductance pressure or reactance drop (equation 2 on page 1,474) gives $E_i = 5.65 \times 10 = 56.5$ volts.

In fig. 2,088, lay of AB=50 volts, and BC=56.6 volts. Using a scale of 20 volts to the inch gives AB=2.5 ins., and BC=2.83 ins. Joining AC gives the impressed voltage, which by measurement is 75.4 volts.

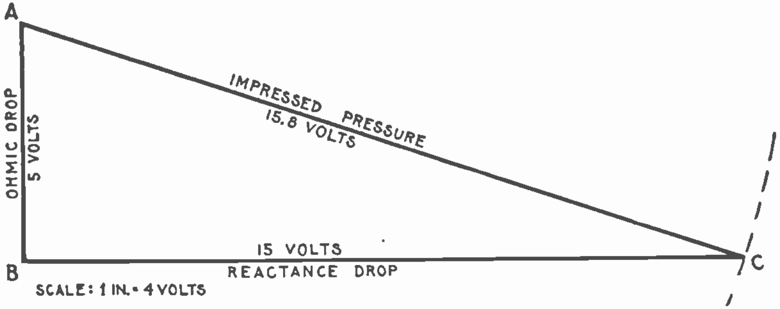


FIG. 2,085.—Diagram for obtaining reactance drop in circuit containing 5 volts ohmic drop. and 15.8 volts impressed pressure.

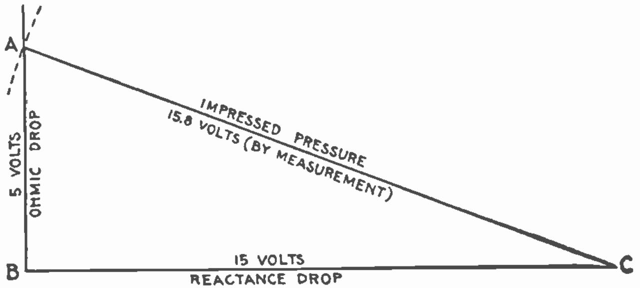


FIG. 2,086.—Diagram for obtaining ohmic drop in the circuit fig. 2,084 when impressed pressure and reactance drop are given. Lay off BC, to scale = reactance drop; draw AB, at right angles and of indefinite length; with C, as center and radius of length = impressed pressure, describe an arc cutting ohmic drop line at A, then AB = ohmic drop = 5 volts by measurement.

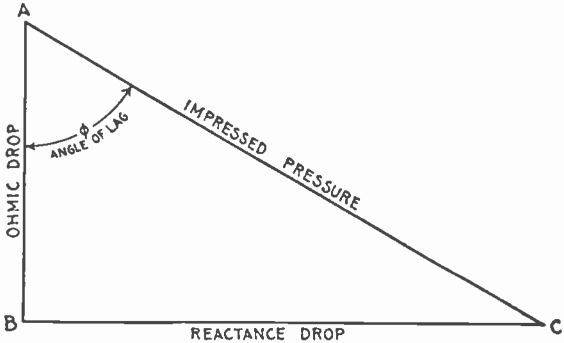


FIG. 2,087.—Graphical method of finding angle of lag when the ohmic drop and reactance drop are given. The angle of lag ϕ, is that angle included between the impressed pressure and the ohmic drop lines, that is, between AC and AB.

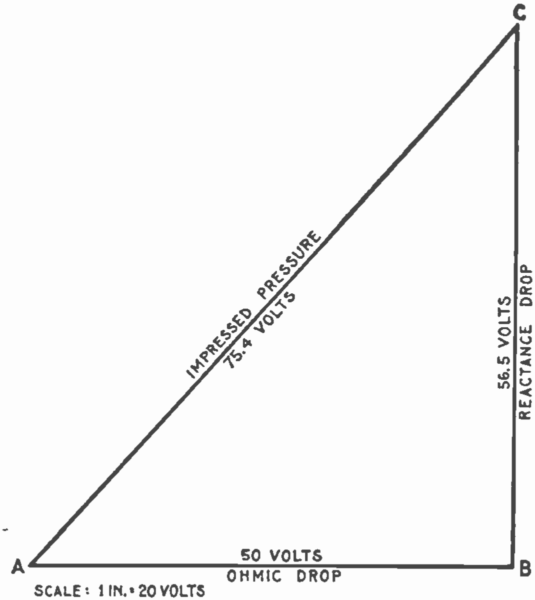


FIG. 2,088.—Diagram for impressed pressure on circuit containing 5 ohms resistance and inductance of 15 milli-henrys, the current being 10 amperes with frequency of 60.

In some problems it is required to find the impedance of a circuit in which the ohmic and spurious resistances are given. This is done in a manner similar to finding the impressed pressure.

Ohmic resistance and spurious resistance or inductance reactance both tend to reduce an alternating current. Their

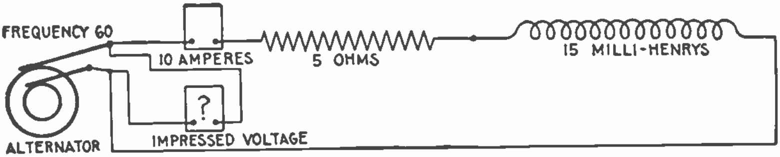


FIG. 2,089.—Diagram of circuit containing 5 ohms resistance, 15 milli-henrys inductance, with 8 ampere 60 frequency current.

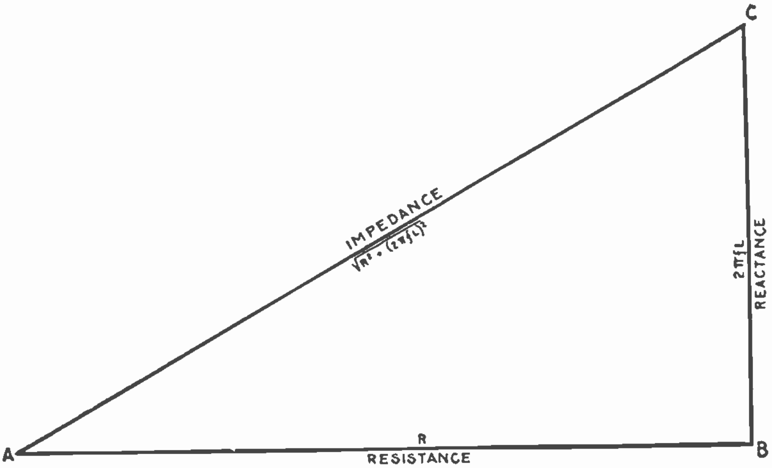


FIG. 2,090.—Graphical method of obtaining the impedance in circuits containing resistance and inductance, having given the resistance and reactance, that is, the ohmic resistance and spurious resistance. With any convenient scale lay off AB = *resistance*, and erect the perpendicular BC = *reactance* (using the same scale); join AC, whose length (measured with the same scale) will give the *impedance*.

combined action or impedance is equal to the square root of the sum of their squares, that is,

$$impedance = \sqrt{resistance^2 + reactance^2}$$

This relation is represented graphically by the side of a right angle triangle as in fig. 2,090, in which the hypothenuse corresponds to the impedance, and the sides to the resistance and reactance.

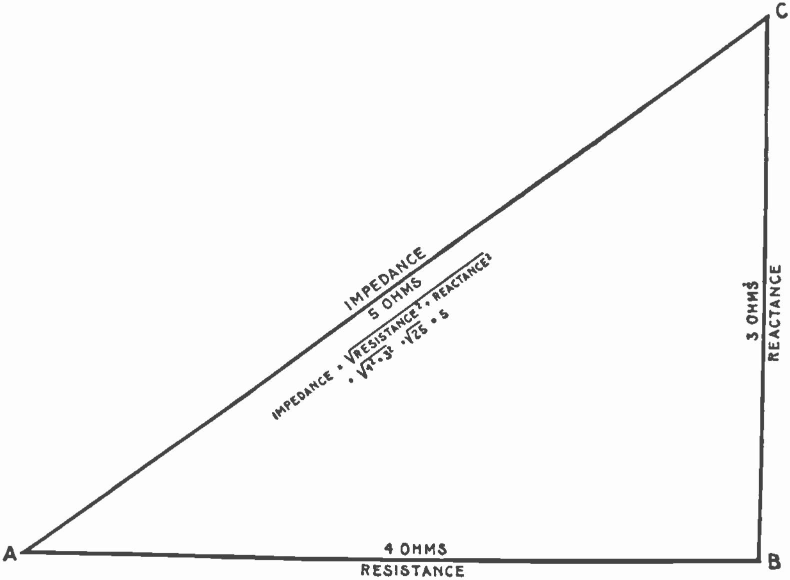


Fig. 2,091.—Diagram for obtaining the impedance of a circuit containing 4 ohms resistance and 3 ohms reactance.

Example.—In a certain circuit the resistance is 4 ohms, and the reactance 3 ohms. What is the impedance?

In fig. 2,091, lay off, on any scale AB = 4 ohms and erect the perpendicular BC = 3 ohms. Join AC, which gives the impedance, and which is, measured with the same scale, 5 ohms.

Example 1.—A coil of wire has a resistance of 20 ohms and an inductance of 15 milli-henrys. What is its impedance for a current having a frequency of 100?

The ohmic value of the inductance, that is, the reactance is

$$2\pi f L = 2 \times 3.1416 \times 100 \times .015 = 9.42 \text{ ohms.}$$

In fig. 2,092, lay off, on any scale, AB = 20 ohms, and the perpendicular BC to length = 9.42 ohms. Join AC, which gives the impedance, which is, measured on the same scale, 22.1 ohms.

Example 2.—What is the angle of lag in a circuit having a resistance of 4 ohms and a reactance of 3 ohms?

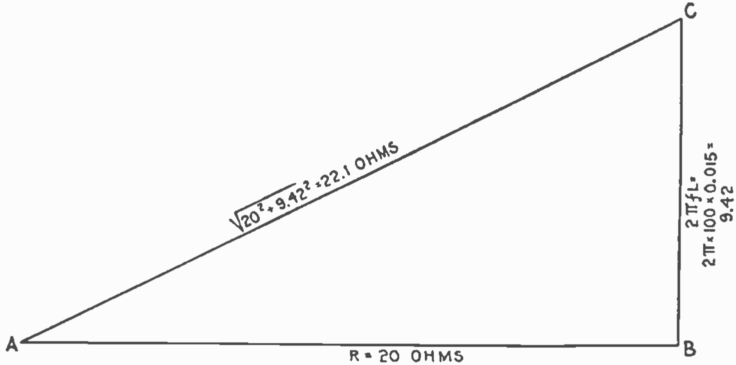


FIG. 2,092.—Diagram for impedance of circuit containing 20 ohms resistance, and inductance of 15 millihenrys, when the frequency is 100.

Construct the impedance diagram in the usual way as in fig. 2,093, then the angle included between the impedance and resistance lines (denoted by ϕ) is the angle of lag, that is, the angle BAC. By measurement with a protractor it is 37 degrees. By calculation the tangent of the angle of lag or

$$\tan \phi = \frac{BC}{BA} = \frac{3}{4} \text{ or } .75$$

From the table on page 921, the angle is approximately 37°.

Circuits Containing Resistance and Capacity.—The effect of capacity in an alternating current circuit is to cause the current to lead the pressure, since the reaction of a condenser, instead of tending to prolong the current, tends to drive it back.

Careful distinction should be made between capacity *in series* with a circuit and capacity *in parallel* with a branch of a circuit. The discussion here refers to capacity in series, which means that the circuit is not continuous but the ends are joined to a condenser, as shown at the right in fig. 2,094, so that no current can flow except into and out of the condenser.

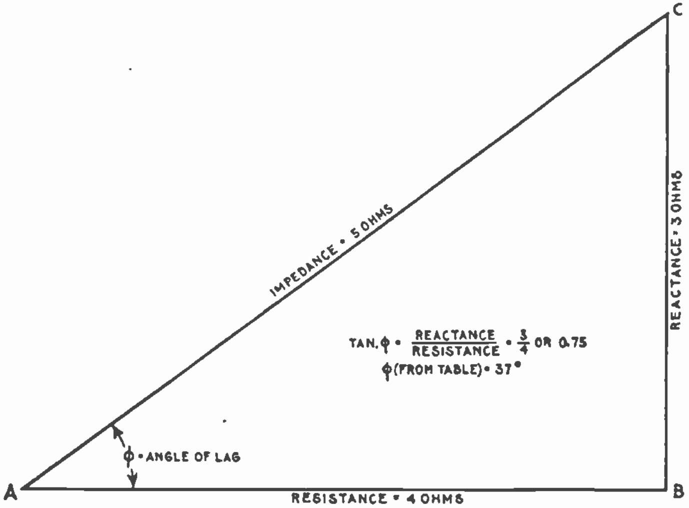


FIG. 2,093.—Diagram showing angle of lag for current containing 4 ohms resistance and 3 ohms reactance.

Ques. In circuits containing resistance and capacity upon what does the amount of lead depend?

Ans. Upon the relative values of the resistance and the capacity reactance.

Ques. Describe the action of a condenser when current is applied.

Ans. When the current begins to flow into a condenser, that is, when the flow is maximum, the back pressure set up by the condenser (called the *condenser pressure*) is zero, and when the flow finally becomes zero, the condenser pressure is maximum.

Ques. What does this indicate?

Ans. It shows that the phase difference between the wave representing the condenser pressure and the current is 90°, as illustrated in fig. 2,095.

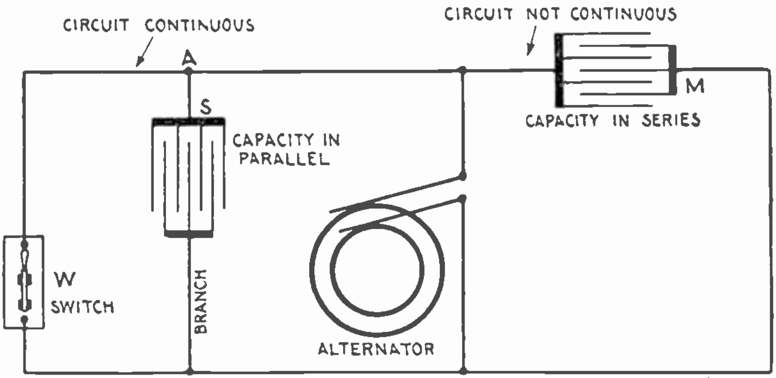


Fig. 2,094.—Circuit diagram illustrating the distinction between *capacity in series* and *capacity in parallel*. The condition for *capacity in series* is that the circuit must be discontinuous as at M; for *capacity in parallel* the main circuit must be continuous; this means that the capacity must be inserted in a branch of the main circuit as at A. In the figure the capacity S. is connected *in series* with respect to the branch, that is, the branch is discontinuous, but it is *in parallel* with respect to the main circuit, when the latter is continuous, that is, when the switch W, is closed. If W, be opened, the main circuit becomes discontinuous and S, is changed from *in parallel* to *in series* connection.

Ques. Is the condenser pressure ahead or behind the current and why?

Ans. It is ahead of the current. The condenser pressure, when the condenser is discharged being zero, the current enters at a maximum velocity as at *A*, in fig. 2,095, and gradually decreases to zero as the condenser pressure rises to maximum at B, this change taking place in one-quarter period. Thus the condenser pressure, which opposes the current, being at a maximum when the current begins its cycle is 90° *ahead of the current*, as is more clearly seen in the last quarter of the cycle (fig. 2,095).

Ques. What is the phase relation between the condenser

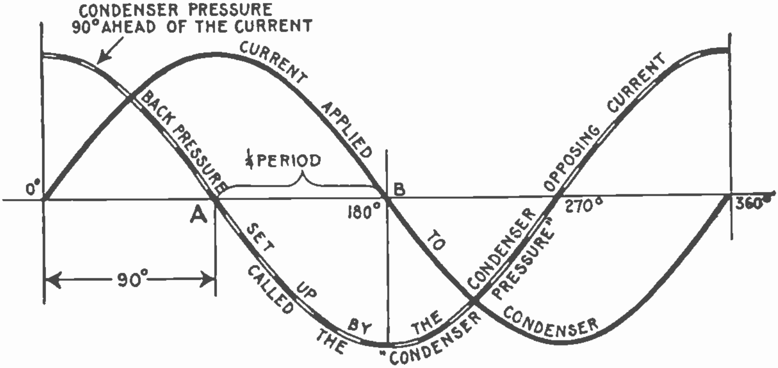


FIG. 2,095.—Current and pressure curves showing that the condenser pressure is 90° ahead of the current. A current flowing into a condenser encounters a gradually increasing pressure which opposes it, beginning from zero pressure when the current enters at maximum flow and increasing to the same value as the current pressure, at which time the current ceases to flow. Hence, since the current varies from zero to maximum in one quarter period, or 90°, the phase difference between current and condenser pressure is 90°. The condenser pressure reaching a positive maximum when the current starts from zero on the positive wave, is 90° ahead of the current.

pressure and the pressure applied to the condenser to overcome the condenser pressure?

Ans. The pressure applied to the condenser to overcome the condenser pressure, or as it is called, the *capacity pressure*, must be opposite to the condenser pressure, or 90° *behind the current*.

In circuits containing resistance and capacity, the total pressure impressed on the circuit, or *impressed pressure*, as it is called, is made up of two components:

1. The *active pressure*, or pressure necessary to overcome the resistance;

The active pressure is in phase with the current.

2. The *capacity pressure*, or pressure necessary to overcome the condenser pressure.

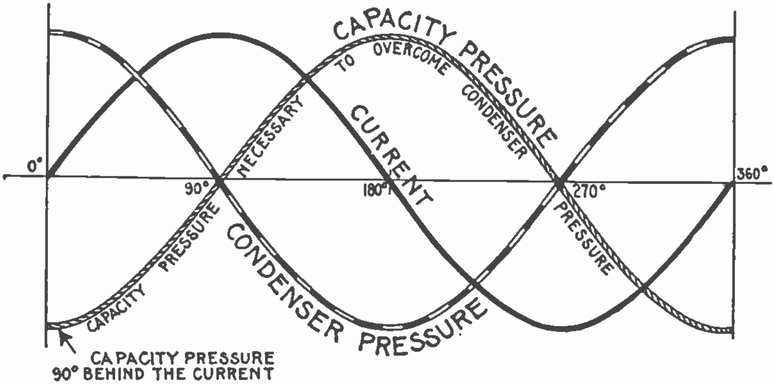


FIG. 2,096.—Current and pressure curves, showing phase relation between the current, condenser pressure, and impressed or *capacity* pressure necessary to overcome the condenser pressure. The capacity pressure, since it must overcome the condenser pressure, is equal and opposite to the condenser pressure, that is, the phase difference is 180°. The condenser pressure being 90° *ahead* of the current, the impressed pressure is 90° *behind* the current.

The capacity pressure is 90° behind the current.

Problems involving resistance and capacity are solved similarly to those including resistance and inductance.

The Active Pressure, or "Ohmic Drop."—This, as before explained is represented, in fig. 2,097, by a line AB, which in magnitude equals, by Ohm's law, the product of the resistance multiplied by the current, that is,

$$E_a = R_o I_v \text{.............................} (1)$$

The Capacity Pressure or "Reactance Drop."—This component of the impressed pressure, is, applying Ohm's law,

capacity pressure = capacity reactance × virtual current.

$$E_c = X_c I_v \text{.............................} (2)$$

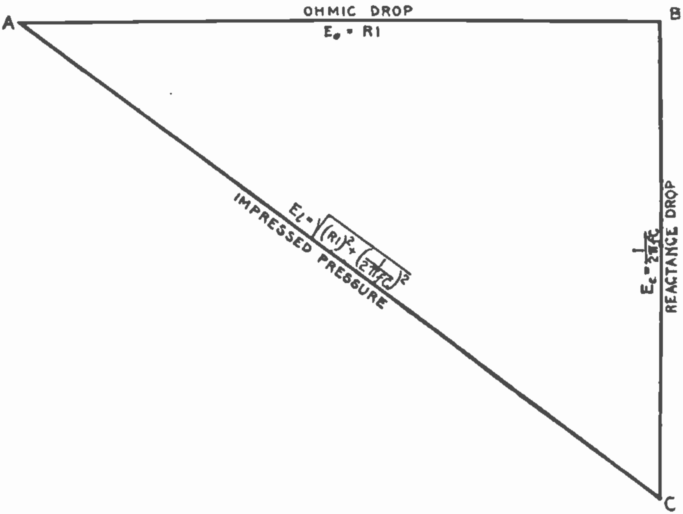


FIG. 2,097.—Graphical method of obtaining the impressed pressure in circuits containing resistance and capacity, having given the ohmic drop and reactance drop due to capacity. With any convenient scale, lay off AB = *ohmic drop*, and at right angles to AB, draw BC = *reactance drop* (using the same scale). Join AC, whose length (measured with the same scale) will give the *impressed pressure*. The mathematical expressions for the three quantities are given inside the triangle, and explained in the text.

In this, the expression for capacity reactance X_c, that is, for the value of capacity in ohms is, as explained on page 1,435,

$$X_c = \frac{1}{2\pi f C} \text{.........................} (3)$$

Substituting this value of X_c in equation (2) and writing I for virtual current.

$$E_C = \frac{I}{2\pi f C} \quad \text{.................. (4)}$$

CAUTION—The reader should distinguish between the 1 (one) in (3) and the letter I in (4); which look alike.

Since the capacity pressure is 90° *behind* the current, it is represented in fig. 2,097, by a line BC, drawn *downward*, at right angles to AB, and of a length corresponding to the capacity pressure, that is, to the reactance drop.

The Impressed Pressure.—Having determined the ohmic and reactance drops and represented them in the diagram, fig. 2,097, by lines

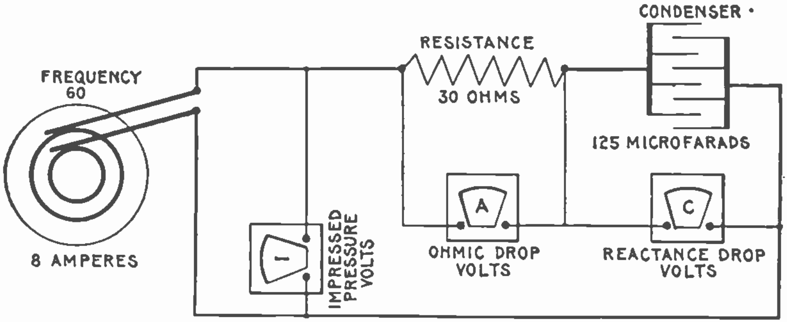


FIG. 2,098.—Diagram of circuit containing a resistance of 30 ohms and capacity of 125 microfarads. The calculation for impressed pressure, ohmic drop, and reactance drop for a current of 8 amperes at frequency 60 is given in the example given below, the diagram for impressed pressure being given in fig. 2,099.

AB and BC, respectively, a line AC, joining A and C, will then be the resultant of the two component pressures, that is, it will represent the *impressed pressure* or total pressure applied to the circuit.

In the diagram it should be noted that the active pressure is called the *ohmic drop*, and the capacity pressure, the *reactance drop*.

Example 1.—A circuit as shown in fig. 2,098 contains a resistance of 30 ohms, and a capacity of 125 microfarads. If an alternating current of 8 amperes with frequency 60 be flowing in the circuit, what is the ohmic drop, the reactance drop, and the impressed pressure?

The ohmic drop or active pressure is, substituting in formula (1) on page 1,485,

$$E_a = 30 \times 8 = 240 \text{ volts}$$

which is the reading of voltmeter A in fig. 2,098.

The reactance drop or

$$E_c = \frac{I}{2\pi f C} = \frac{8}{2 \times 3.1416 \times 60 \times .000125} = 170 \text{ volts}$$

in substituting, note that the capacity C of 125 microfarads is reduced to .000125 farad.

Using a scale of say 1 inch = 80 volts, lay off in fig. 2,099, AB, equal to the ohmic drop of 240 volts; on this scale AB = 3 inches. Lay off at

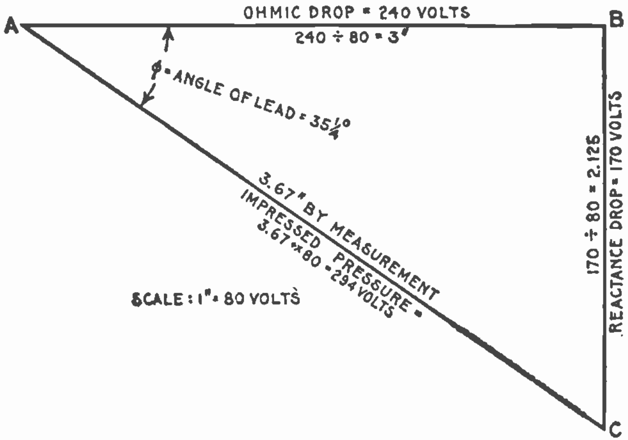


FIG. 2,099.—Diagram for obtaining the impressed pressure of the circuit shown in fig. 2,098.

right angles, BC = reactance drop = 170 volts = 2.125 inches. Join AC, which gives the impressed voltage (that is the reading of volt meter I in fig. 2,098), which measures 294 volts.

By calculation, impressed pressure = $\sqrt{240^2 + 170^2} = 294$ volts.

Example 2.—In the circuit shown in fig. 2,098, what is the angle of lead?

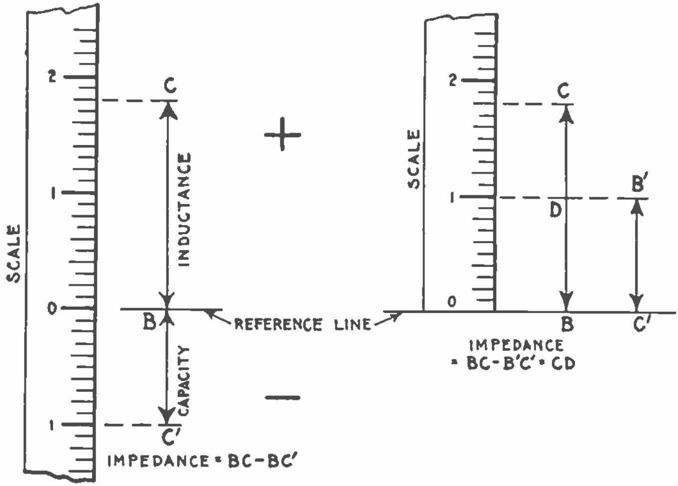
The tangent of the angle of lead is given by the quotient of the reactance divided by the resistance of the circuit. That is,

$$\tan\phi = \frac{reactance}{resistance} = \frac{reactance\ drop}{resistance\ drop}$$

$$\tan\phi = \frac{E_c}{E_a} = \frac{I}{2\pi f C} \div E_a \qquad (1)$$

The tangent is given a negative sign because lead is opposed to lag and because the positive value is assigned to lag. Substituting in (1)

$$\tan\phi = \frac{170}{240} \text{ or } \frac{2.125}{3} = -.71$$



FIGS. 2,100 and 2,101.—Diagrams for circuits containing inductance and capacity. Since inductance and capacity act 180° apart, their reactances, or their ohmic drops may be represented by oppositely directed lines. These may be drawn above and below a reference line, as in fig. 2,100, and their algebraic sum taken, or both may be drawn on the same side of the reference lines and their difference in lengths, as C D, fig. 2,101, measured. Recourse to a diagram for obtaining the resultant reactance in circuits containing inductance and capacity is unnecessary as it is simply a matter of taking the difference of two quantities.

the angle corresponding is approximately 35¼° (see table page 921).

Circuits Containing Inductance and Capacity.—The effect of capacity in a circuit is exactly the opposite of inductance, that is, one tends to neutralize the other. The method of representing each graphically has been shown in the preceding figures. Since they act oppositely, that is 180° apart, the reactance due to each may be calculated and the values thus found, represented by oppositely directed vertical lines: the inductance resistance upward from a reference line, and the capacity resistance downward from the same reference line. The difference then is the resultant impedance. This method is shown in fig. 2,100, but it is more conveniently done as in fig. 2,101.

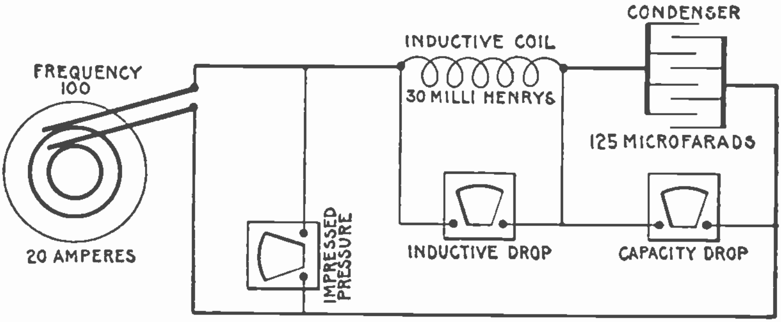


Fig. 2,102.—Diagram of circuit containing 30 millihenrys inductance and 125 microfarads capacity, with current of 20 amperes, 100 frequency.

Example 1.—In a circuit, as in fig. 2,102, containing an inductance of 30 milli-henrys and a capacity of 125 microfarads, how many volts must be impressed on the circuit to produce a current of 20 amperes having a frequency of 100.

The inductance reactance is

$$X_i = 2\,\pi\,f\,L = 2\times3.1416\times100\times.03 = 18.85 \text{ ohms.}$$

Substituting this and the current value of 20 amperes in the formula for inductance pressure

$$E_i = R_i I = 18.85\times20 = 377 \text{ volts.}$$

Reducing 125 microfarads to .000125 farad, and substituting in the formula for capacity pressure

$$E_c = \frac{I}{2\pi f C} = \frac{20}{2 \times 3.1416 \times 100 \times .000125} = 255 \text{ volts.}$$

A diagram is unnecessary in obtaining the impressed pressure since it is simply the difference between inductance pressure and capacity pressure (the circuit being assumed to have no resistance), that is

$$\text{impressed pressure} = E_l - E_c = 377 - 255 = 122 \text{ volts.}$$

Example 2.—A circuit in which a current of 20 amperes is flowing at a frequency of 100, has an inductance reactance of 18.25 ohms, and a capacity of 125 microfarads. What is the impedance?

The reactance due to capacity is

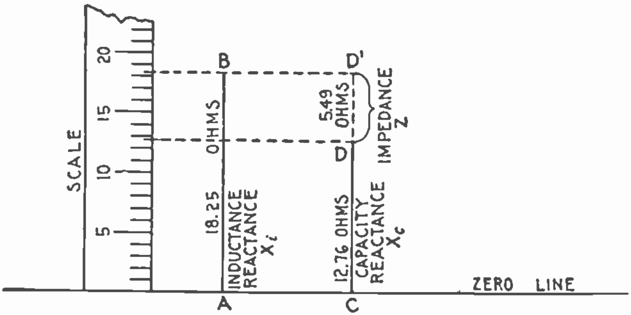


FIG. 2,103.—Impedance diagram for circuit (of above example) containing inductance and capacity. With any convenient scale, erect a perpendicular AB = 18.25 ohms, and CD = 12.76 ohms. Continue CD by dotted line to D′ so that CD′ = AB, then DD′ = AB − CD = inductance reactance − capacity reactance, which is equal to the impedance. Expressed by letters $Z = X_l - X_c = DD'$, which by measurement = 5.49 ohms.

$$X_c = \frac{1}{2\pi f C} = \frac{1}{2 \times 3.1416 \times 100 \times .000125} = 12.76 \text{ ohms.}$$

The impedance of the circuit then is the difference between the two reactances, that is impedance = inductance reactance − capacity reactance, or

$$Z = X_l - X_c = 18.25 - 12.76 = 5.49 \text{ ohms.}$$

Circuits Containing Resistance, Inductance, and Capacity.—When the three quantities resistance, inductance, and capacity, are present in a circuit, the combined effect is easily understood by remembering that *inductance and capacity always act oppositely, that is, they tend to neutralize each other.*

Hence, in problems involving the three quantities, the resultant of inductance and capacity is first obtained, which, together with the resistance, is used in determining the final effect.

Capacity introduced into a circuit containing inductance reduces the latter and if enough be introduced, inductance will be neutralized, giving a resonant circuit which will act as though only resistance were present.

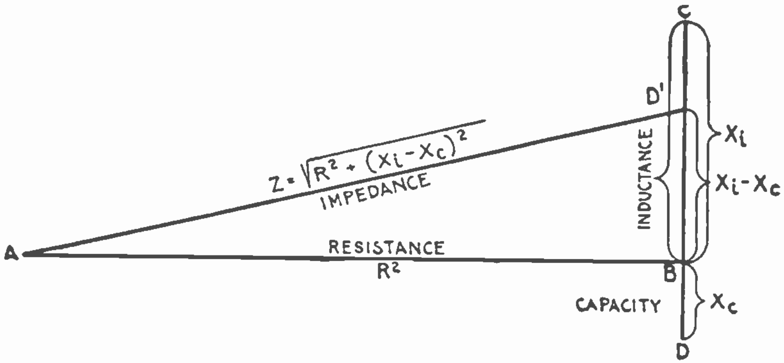


FIG. 2,104.—Impedance diagram for circuit containing resistance, inductance and capacity. The symbols correspond to those used in equation (1) below. In constructing the diagram from the given values, lay off AB =resistance; at B, draw a line at right angles, on which lay off above the resistance line, BC =inductive reactance, and below, BD =capacity reactance, then the resultant reactance =BC −BD =BD′. Join A and D′, then AD′ =impedance.

Ques. What is the expression for impedance of a circuit containing resistance, inductance and capacity?

Ans. It is equal to *the square root of the sum of the resistance squared plus the square of inductance reactance minus capacity reactance.*

This is expressed plainer in the form of an equation as follows:

$$impedance = \sqrt{resistance^2 + (inductance\ reactance - capacity\ reactance)^2}$$

or, using symbols,

$$Z = \sqrt{R^2 + (X_i - X_c)^2} \quad \text{.......} (1)$$

Ques. If the capacity reactance be larger than the inductance reactance, how does this affect the sign of $(X_i - X_c)^2$?

Ans. The sign of the resultant reactance of inductance and capacity will be negative if capacity be the greater, but since

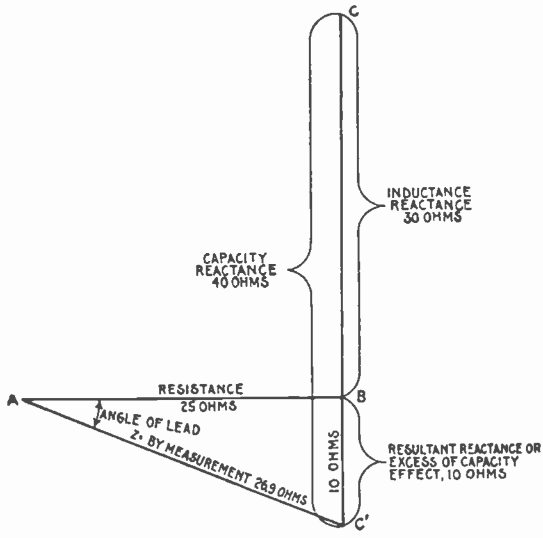


FIG. 2,105.—Impedance diagram of a circuit containing 25 ohms resistance, 30 ohms inductance, and 40 ohms capacity. The resultant reactance being due to excess of capacity, the impedance line AC′ falls *below* the horizontal line AB, indicating that the current *leads* pressure.

in the formula the reactance is squared, the sign will be positive.

Example 1.—What is the impedance in a circuit having 25 ohms resistance, 30 ohms inductance reactance, and 40 ohms capacity reactance?

To solve this problem graphically, draw the line AB, in fig. 2,105, equal to 25 ohms resistance, using any convenient scale.

At B, draw upward at right angles BC = 30 ohms; draw from C, downward CC′ = 40 ohms. This gives—BC′ = CC′ − BC showing the capacity reactance to be 10 ohms in excess of the inductance reactance. Such a circuit is equivalent to one having no inductance but the same resistance and 10 ohms capacity reactance.

The diagram is completed in the usual way by joining AC′, giving the required impedance, which by measurement is 26.9 ohms.

By calculation, $Z = \sqrt{25^2 + (30-40)^2} = \sqrt{25^2 + (-10)^2} = 26.9$

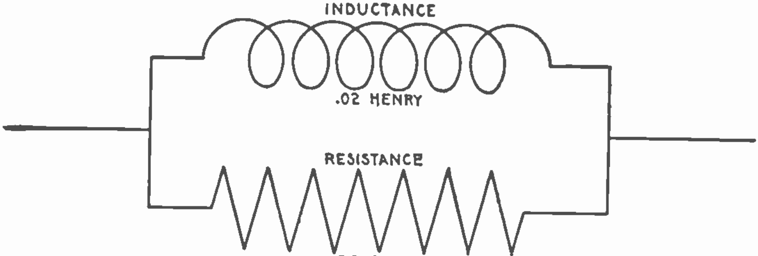


Fig. 2,106.—*Example:* A resistance of 20 ohms and an inductance of .02 henry are connected in parallel as in the diagram. What is the impedance, and how many volts are required for 50 amperes, when the frequency is 78.6? *Solution:* The time constants are not alike, hence the geometric sum of the reciprocals must be taken as the reciprocal of the required impedance. That is, the combined conductivity will be the hypothenuse of the right triangle, of which the ohmic conductivity and the reactive conductivity are the two sides, respectively. Accordingly: $\frac{1}{R} = \frac{1}{20} = .05$, and $\frac{1}{2\pi f L} = \frac{1}{10} = .1$, from which $\frac{1}{R} = \sqrt{\left(\frac{1}{R_1}\right)^2 + \left(\frac{1}{2\pi f L}\right)^2} = .111$. Whence $Z = \frac{1}{.111} = 9$ ohms.

Form of Impedance Equation Without Ohmic Values.—Using the expressions $2\pi f L$ for inductance reactance and $\frac{1}{2\pi f C}$ for capacity reactance, and substituting in equation (1) on page 1,492 gives the following:

$$Z = \sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f C}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

which is the proper form of equation (1) to use in solving problems in which the ohmic values of inductance and capacity must be calculated.

Example 1.—A current has a frequency of 150. It passes through a circuit, as in fig. 2,107, of 23 ohms resistance, of 41 millihenrys inductance, and of 51 microfarads capacity. What is the impedance?

The inductance reactance or

$$X_i = 2\,\pi\,f\,L = 2\times3.1416\times150\times.041 = 38.64 \text{ ohms}$$

(note that 41 henrys are reduced to .041 henry before substituting in the above equation).

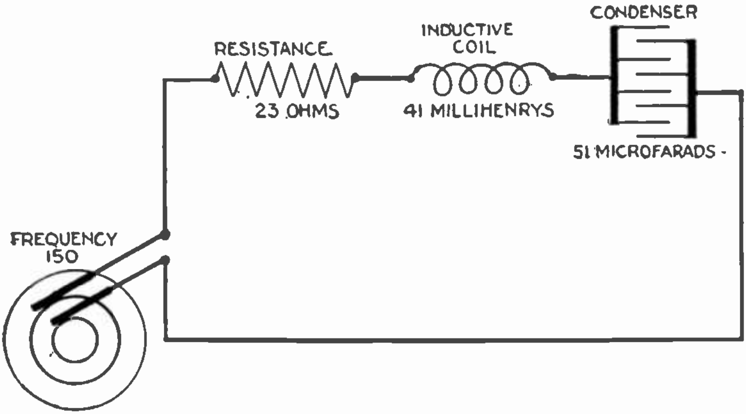


FIG. 2,107.—Diagram of circuit containing 23 ohms resistance, 41 millihenrys inductance, and 51 microfarads capacity, with current supplied at a frequency of 150.

The capacity reactance, or

$$X_c = \frac{1}{2\,\pi\,f\,C} = \frac{1}{2\times3.1416\times150\times.000051} = 20.8 \text{ ohms}$$

(note that 51 microfarads are reduced to .000051 farad before substituting in the above equation).

Substituting the values as calculated for $2\,\pi\,f\,L$ and $\frac{1}{2\,\pi\,f\,C}$ in equation

(2) $Z = \sqrt{23^2 + (38.64 - 20.8)^2} = 29.1$ ohms.

To solve the problem graphically, lay off in fig. 2,108, the line AB, equal to 23 ohms resistance, using any convenient scale. Draw upward and at right angles to AB, the line BC = 38.64 ohms inductance reactance, and from C, lay off downward CC′ = 20.8 ohms capacity reactance. The resultant reactance is BC′, and being above the horizontal line AB, shows that inductance reactance is in excess of capacity reactance by the amount BC′. Join AC′, which gives the impedance sought, and which by measurement is 29.1 ohms.

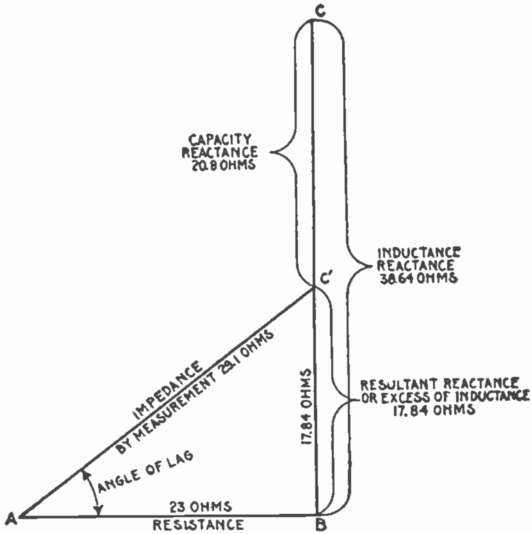


FIG. 2,108.—Impedance diagram for the circuit shown in fig. 2,107. Note that the resultant reactance being due to excess of inductance, the impedance line AC′, falls *above* the horizontal line AB. This indicates that the current *lags* behind the pressure.

In order to obtain the **impressed pressure in circuits containing resistance, inductance and reactance,** an equation similar to (2) on page 1,493 is used which is made up from the following:

$$E_o = RI \qquad (3)$$

$$E_i = 2\pi f LI \quad \ldots\ldots (4)$$

$$E_c = \frac{I}{2\pi f C} \quad \ldots\ldots (5)$$

When all three quantities, resistance, inductance, and capacity are present, the equation is as follows:

$$\textit{impressed pressure} = \sqrt{\textit{ohmic drop}^2 + (\textit{inductive drop} - \textit{capacity drop})^2}$$

$$E_{tm} = \sqrt{E_o^2 + (E_i - E_c)^2} \quad \ldots\ldots (6)$$

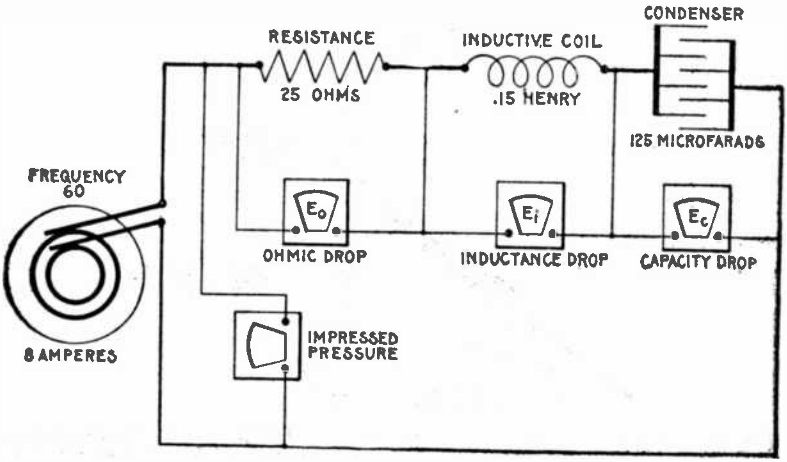


FIG. 2,109.—Diagram of circuit containing 25 ohms resistance, .15 henry inductance, and 125 microfarads capacity, with current of 8 amperes at 60 frequency.

Substituting in this last equation (6), the values given in (3), (4) and (5)

$$E_{tm} = \sqrt{R^2I^2 + \left(2\pi f LI - \frac{I}{2\pi f C}\right)^2}$$

$$= I\sqrt{R^2 + \left(2\pi f L - \frac{1}{2\pi f C}\right)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Ques. What does the quantity under the square root sign in equation (7) represent?

Ans. It is the impedance of a circuit possessing resistance, inductance, and capacity.

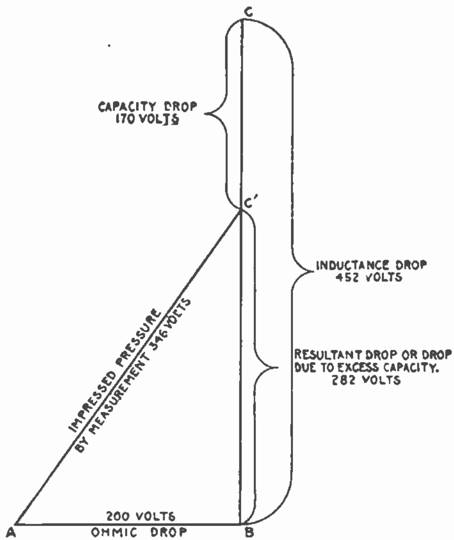


FIG. 2,110.—Diagram for finding the pressure necessary to be impressed on the circuit shown in fig. 2,109, to produce a current of 8 amperes.

Ques. Why?

Ans. Because it is that quantity which multiplied by the current gives the pressure, which is in accordance with Ohm's law.

Example.—An alternator is connected to a circuit having, as in fig. 2,109, 25 ohms resistance, an inductance of .15 henry, and a capacity of 125 microfarads. What pressure must be impressed on the circuit to allow 8 amperes to flow at a frequency of 60?

The ohmic drop is

$$E_o = RI = 25 \times 8 = 200 \text{ volts.}$$

The inductance drop is

$$E_i = 2\pi f LI = 2 \times 3.1416 \times 60 \times .15 \times 8 = 452 \text{ volts.}$$

The capacity drop is

$$E_c = \frac{I}{2\pi f C} = \frac{8}{2 \times 3.1416 \times 60 \times .000125} = 170 \text{ volts.}$$

Substituting the values thus found,

$$\begin{aligned} \text{impressed pressure} &= \sqrt{E^2_o + (E_i - E_c)^2} \\ &= \sqrt{200^2 + (452 - 170)^2} \\ &= \sqrt{200^2 + 282^2} \\ &= \sqrt{119524} \\ &= 345.7 \text{ volts.} \end{aligned}$$

TEST QUESTIONS

1. *What are alternating current diagrams?*
2. *Explain the properties of a right angle triangle.*
3. *How are forces represented by lines?*
4. *Explain the composition of forces.*
5. *Define the terms* resultant *and* components.

6. *In circuits containing resistance and inductance what two components make up the impressed pressure?*
7. *Why is the active pressure in phase with the current?*
8. *In circuits containing resistance and capacity upon what does the amount of lead depend?*
9. *Describe the action of a condenser when current is applied.*
10. *Is the condenser pressure ahead or behind the current, and why?*
11. *What is the phase relation between the condenser pressure and the pressure applied to the condenser to overcome the condenser pressure?*
12. *Name the two components which make up the impressed pressure in circuits containing resistance and capacity.*
13. *How is the inductance reactance found in circuits containing inductance and capacity?*
14. *Is a diagram necessary to obtain the impressed pressure?*
15. *What is the expression for impedance of a circuit containing resistance, inductance and capacity?*
16. *If the capacity reactance be larger than the inductance reactance, how does this affect the sign of* $(X_i - X_c)^2$?
17. *Give the form of impedance equation without ohmic values.*
18. *When all three quantities, resistance, inductance and capacity, are present, what is the equation for the impressed pressure?*

19. *What does the quantity under the square root sign in the equation for impressed pressure, represent?*
20. *Give the examples, for the various circuits.*

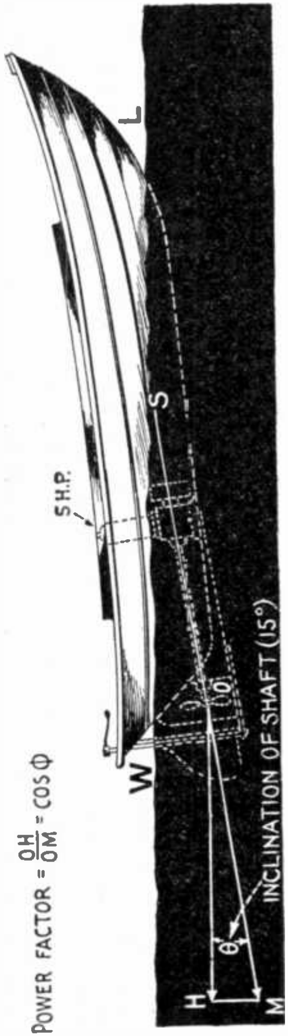


FIG. 2,111.—Marine analogy of *power factor*. *1.* Usually the propeller shaft in a dory is at a considerable angle to the surface of the water, hence the full thrust of the propeller wheel is not effective in propelling the dory. The power of the engine then must be multiplied by a coefficient (less than unity) called the *power factor* to obtain the true or net power. On MS, take OM = thrust and draw from M, a vertical line to meet a horizontal line from O, at H. OH, then, is the active component of the thrust serving to move the boat, the power of the engine being reduced in the proportion of OH ÷ OM, but this is the *cosine* of angle ϕ, hence power factor = *cos* ϕ. *Example.* The dory has a 5 *h.p.* engine (*kva* ÷ 746) with shaft inclined 15° (angle ϕ), what is the power factor, and net power (*true watts* ÷ 746) effective in propelling the dory? Power factor = cos ϕ = (from table), .966. Net power = (*kva* ÷ 746 × *power factor*) = 5 × .966 = 4.83 *h.p.*, 5 − 4.85 = .17 *h.p.* being lost because of inclination of shaft. The foregoing neglects the additional loss due to inefficiency of the propeller.

CHAPTER 49

The Power Factor

The determination of the power in a direct current circuit is a simple matter since it is only necessary to multiply together the volts and amperes to obtain the output in watts.

In the case of alternating current circuits, this holds true only when the current is in phase with the pressure —a condition rarely found in practice.

When the current is not in phase with the pressure, the product of volts and amperes as indicated by the volt meter and ammeter must be multiplied by a coefficient called the *power factor* in order to obtain the *true watts*, or actual power available.

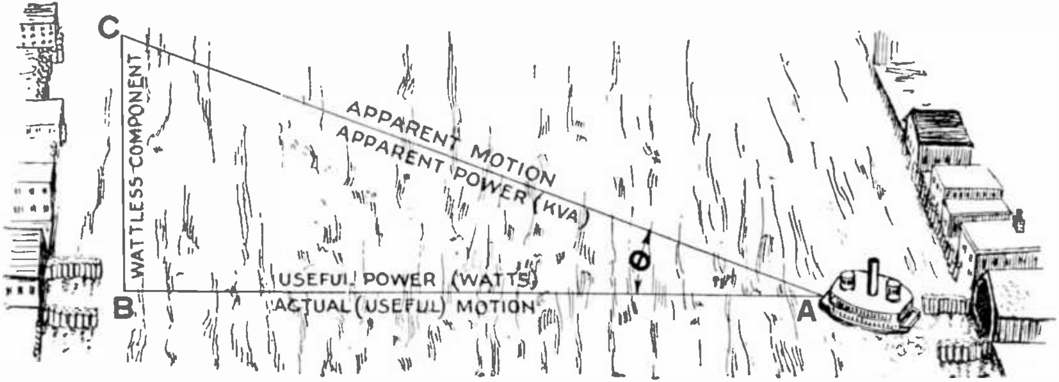


FIG. 2,112.—Marine analogy of power factor. *2.* A ferry boat in crossing a river to a slip B, would head up stream to some point C, to allow for the effect of the tide. Under these conditions, the actual motion is from A, to B, and the apparent motion from A, to C. Accordingly when the tide is running in the direction from C, toward B, the energy required to propel the ferry from A, to B, is equal to that required to propel it from A, to C, in still water. The effect of the tide is the same as that of inductance or capacity in an alternating circuit, that is, it puts the applied force or thrust (impressed volts) out of phase with the motion of the boat (amperes), this phase difference being indicated by the angle BAC or ϕ. Now, work (watts) is the product of two factors, pressure (volts) and distance (amperes); accordingly the apparent work done in propelling the boat from A, to B is the product of the *thrust of the propeller* multiplied by AC, which in analogy corresponds to the product of volt meter and ammeter readings called *kva*. The *useful* or *true* work, however, in propelling the ferry across stream (tide running) is the product of the thrust of the propeller multiplied by AB, which in analogy corresponds to the watt meter reading. To obtain the *useful* or *true* work the product of the apparent motion AC, × thrust must be multiplied by a coefficient or *power factor* because the thrust is applied at an angle BAC (called ϕ) to the true motion, the power factor being equal to the cosine, of this angle ϕ, or AB ÷ AC. ***Similarly,*** when there is phase difference between pressure and alternating current, the volt meter and ammeter readings must be multiplied by the power factor or cos ϕ, to give the output of an alternator available for external, or useful work (in analogy, propeller thrust × AB) the excess power indicated by ammeter and volt meter readings, performing no external work, but causing objectionable heating of the alternator.

There are several ways of defining the power factor, any of which requires some explanation.

The power factor may be defined as: *The number of watts indicated by a watt meter,*

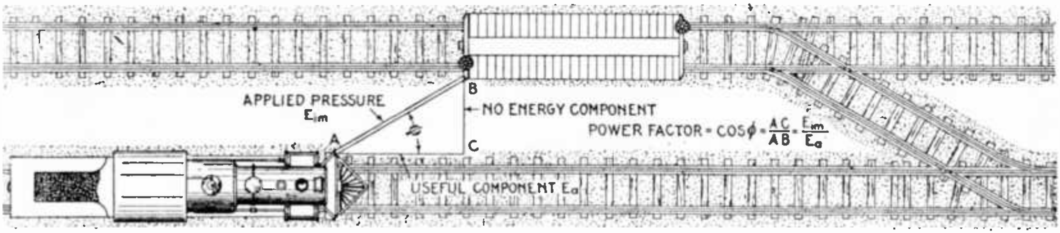


FIG. 2,113.—Mechanical analogy of power factor, as exemplified by a locomotive "poling" a car off a siding. The car and locomotive are shown moving in a parallel direction, and the pole AB, inclined at an angle ϕ. Now, if the length of AB, be taken to represent the pressure exerted on the pole by the locomotive, then the imaginary lines AC and BC, drawn respectively parallel and at right angles to the direction of motion will represent respectively the useful and no energy (wattless) components; that is to say, if the pressure AB, be applied to the car at an angle ϕ, only part of it, AC, is useful in propelling the car, the other component, BC, being wasted in tending to push the car off the track at right angles to the rails, being resisted by the flanges of the outer wheels.

divided by the apparent watts, the latter being the *watts as measured by a volt meter and ammeter*.

The power factor may be expressed as being equal to

$$\frac{\textit{true power}}{\textit{apparent power}} = \frac{\textit{true watts}}{\textit{apparent watts}} = \frac{\textit{true watts}}{\textit{volts} \times \textit{amperes}}$$

Ques. What are the true watts?

Ans. The watts as measured by a watt meter.

Ques. What are the apparent watts?

Ans. The watts obtained by multiplying together the simultaneous volt meter and ammeter readings.

Ques. What is usually meant by power factor?

Ans. The multiplier used with the apparent watts to determine how much of the power supplied is available.

Ques. Upon what does the power factor depend?

Ans. Upon the relative amounts of resistance inductance and capacity contained in the circuit.

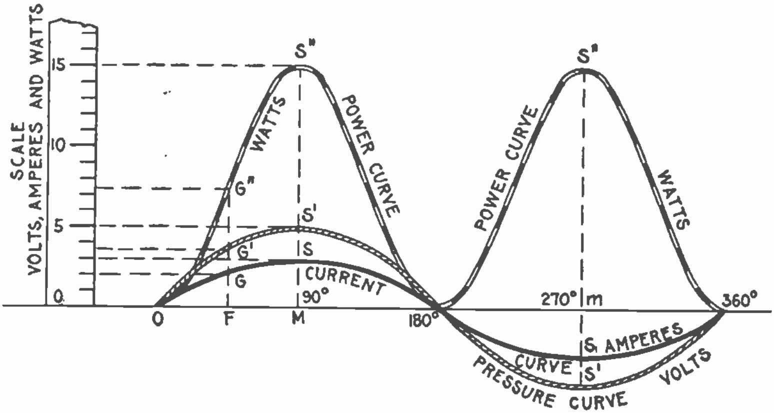


FIG. 2,114.—Method of drawing the power curve from the pressure and current curves. As shown, the same scale is used for all curves. This as a rule, makes the power curve inconveniently high, hence it is usually drawn to smaller scale as in fig. 2,115.

Ques. How does the power factor vary in value?

Ans. It varies from one to zero.

The power factor, as will be shown later, is equal to *the cosine of the angle of phase difference;* its range then is from one to zero because these are the limiting values of the cosine of an angle (neglecting the + or − sign).

Ques. What is the effect of lag or lead of the current on the power factor?

Ans. It causes it to become less than one.

How to Obtain the Power Curve.—Since under any phase condition, the power at any instant is equal to the product of the pressure multiplied by the current at that instant, a curve may be easily plotted from the pressure and current curves, giving the instantaneous values of the power through a complete cycle.

In fig. 2,114, from the zero line of the current and pressure curves, draw any ordinate as at F, cutting the current curve at G, and the pressure curve at G′. The values for current and pressure at this point are from the scale, 2 amperes and 3.7 volts. Since watts = amperes × volts, the ordinate FG, is to be multiplied by ordinate FG′, that is,

$$2 \times 3.7 = 7.4.$$

Project up through F, the ordinate FG″ = 7.4, and this will give one point on the power curve.

Similarly at another point, say M, where the current and pressure are maximum

$$MS \times MS' = MS'', \text{ that is}$$
$$3 \times 5 = 15$$

giving S″, another point on the curve. Obtaining several points in this way the power curve is then drawn through them as shown.

Ques. Why is the power curve positive in the second half of the period when there are negative values of current and pressure?

Ans. Because the product of two negative quantities is positive.

Ques. Does fig. 2,114 represent the usual way of drawing a power curve?

Ans. Since ordinates of the power curve are products of the current and pressure ordinates, they will be of inconvenient length if drawn to the same scale; it is therefore customary to use a different scale for the power ordinates, as in fig. 2,115.

The illustration is lettered identically with fig. 2,114, with which it should be compared.

Synchronism of Current and Pressure; Power Factor Unity.—The current and pressure would be in phase as represented in fig. 2,116 were it possible to have a circuit containing

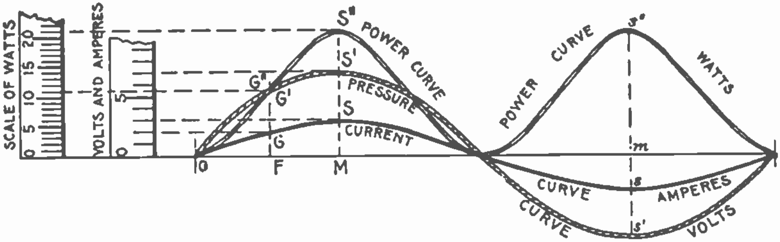


FIG. 2,115.—Usual method of drawing power curve from the pressure and current curves. A smaller scale is employed for the power curve in order to reduce its height.

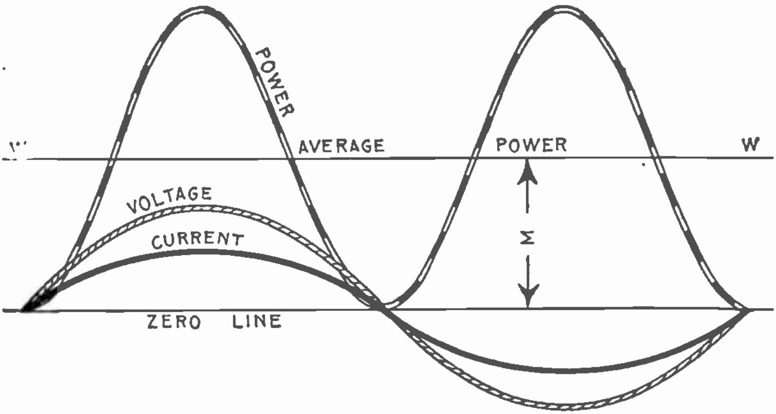


FIG. 2,116.—Synchronism of current and pressure. Power curve showing that the power factor is unity. This is indicated by the fact that the power curve does not project below the base or zero line.

resistance only. In actual practice *all circuits contain at least a small amount of reactance.*

A circuit supplying nothing but incandescent lamps comes very nearly being all resistance, and may be so considered in the discussion here. Fig. 2,117 illustrates a circuit containing only resistance. In such a circuit the pressure and current (as shown in fig. 2,116) pass through zero and through their maximum values together.

Multiplying instantaneous values of volts and amperes will give the power curve, as before explained, whose average value is half-way between the zero line and the maximum of the curve; that part of the power curve above the line of average

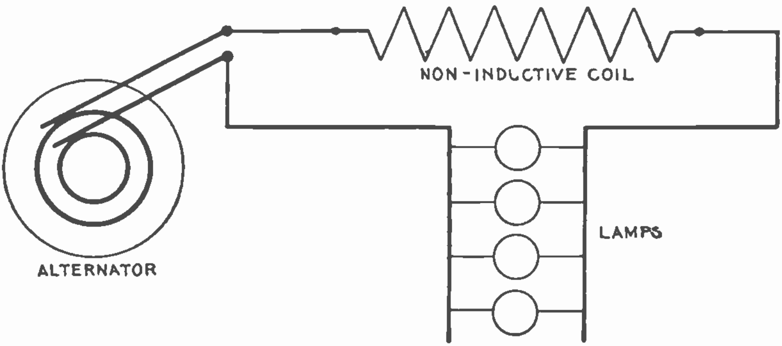


FIG. 2,117.—Diagram of circuit containing only resistance; in such a circuit the power factor is unity.

power WW, exactly filling the open space below the line WW. That is,

$$\text{average power} = \text{maximum power} \div \sqrt{2}$$

$$= \frac{\text{maximum voltage} \times \text{maximum current}}{\sqrt{2}}$$

$$= \text{virtual voltage} \times \text{virtual current.}$$

This latter is simply the product of the volt meter and ammeter readings which give the watts just the same as in direct current.

Ques. What should be noticed about the power curve?

Ans. Its position with respect to the zero line; it lies wholly above the zero line which denotes that all the power delivered to the circuit except that dissipated by friction is useful, that

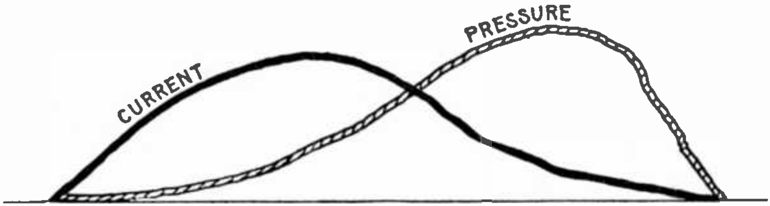


FIG. 2,118.—Case of synchronism of current and pressure with power factor less than unity. Suppose the waves of current and voltage to be in phase, but distorted in form, and not symmetrical, so that they do not run uniformly together, as shown in the figure. Then the real power factor may not be unity, although indicated as such by the power factor meter. However, the switchboard instruments are made to show the angle of lag as the power factor, because the error due to wave distortion is generally too small to be considered.

is, the power factor is unity. Hence, *to keep the power factor as near unity as possible is one of the chief problems in alternating current distribution.*

Ques. Can the power factor be less than unity if the current and pressure be in phase?

Ans. Yes, if the waves of current and voltage be distorted as in fig. 2,118.

Effect of Lag and Lead.—In an alternating circuit the amount of power supplied *depends on the phase relationship of the current and pressure.*

As just explained, when there is synchronism of current and pressure, that is, when they are in phase (as in fig. 2,116) the power factor is unity, assuming no distortion of current and pressure waves. In all other cases the power factor is less than unity, that is, *the effect of lag or lead is to make the power factor less than unity.*

The effect of lag on the power factor may be illustrated by fig. 2,119, in which the angle between the pressure and current, or the angle of lag is taken as 40°, corresponding to a power factor of .766.

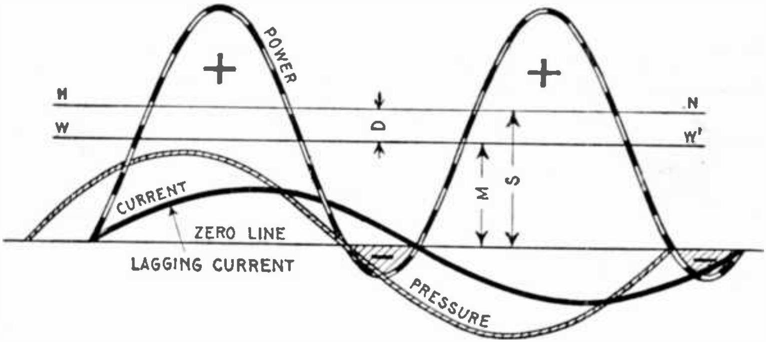


FIG. 2,119.—Effect of lag on the power factor. When the current lags behind the pressure the power factor becomes less than unity. It will be seen that the power curve projects below the zero line giving the shaded area which represents negative power which must be subtracted from the + areas above the zero line to get the net power. In the figure the line WW', is drawn at a height corresponding to the average power, and HN, at a height corresponding to the average power that would be developed if the current were in phase with the pressure. The power factor then is represented by M ÷ S, and by inspection of the figure it is seen that this is less than unity.

Plotting the power curve from the products of instantaneous volts and amperes taken at various points, the power curve is obtained, a portion of which lies below the horizontal line. The significance of this is that at certain times, the current is flowing in the opposite direction to that in which the impressed pressure would send it. During this part of the period conditions are reversed, and the power (indicated by the shaded area), instead of being supplied by the source to the circuit, is being supplied by the circuit to the source.

This condition is exactly analogous to the case of a steam engine, expanding the steam below the back or exhaust pressure, a condition sometimes caused by the action of the governor in considerably reducing the cut off for very light load. An indicator diagram of such steam distribution is shown in fig. 2,121. This gives a negative loop in the diagram indicated by the shaded section.

It must be evident that the average pressure of the shaded loop portion of the diagram must be subtracted from that of the other portion, because during the expansion below the exhaust pressure line, the back pressure is in excess of the forward pressure exerted on the piston by the expanding steam, and the engine would accordingly reverse its motion,

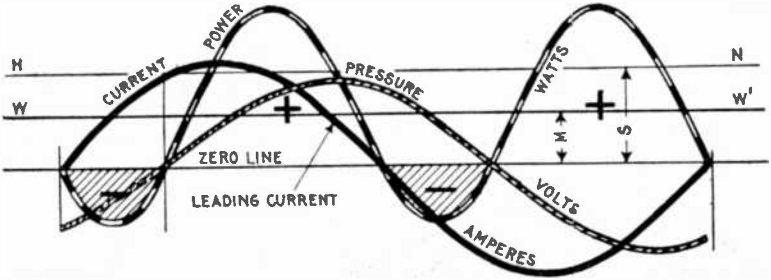


FIG. 2,120.—Effect of lead on the power factor. When the current is in advance of the pressure the power factor becomes less than unity. The curve, as shown, projects below the zero line, giving the shaded area which represents negative power which must be subtracted from the + areas above the zero line to get the net power. As in fig. 2,119, the line WW' at a height M, represents the average power, and HN, the average power for synchronism of current and pressure. The power factor then is M÷S which is less than unity.

were it not for the energy previously stored up in the fly wheel in the form of *momentum*, which keeps the engine moving during this period of back thrust. Evidently the shaded area must be subtracted from the positive area to obtain the net work done during the stroke. Hence following the analogy as far as possible if M, work (watts) be done during each revolution (cycle) when steam does not expand below back pressure (when current and pressure are in phase), and S, negative work (negative watts) be done when steam expands below back pressure (when there is lag), the efficiency (power factor) is (M−S)÷M.

"Wattless Current"; Power Factor Zero.—When the power factor is zero, it means that the phase difference between the current and the pressure is 90°.

The term *wattless current*, as understood, does not indicate an absence of electrical energy in the circuit: its elements are there, but not in an available form for external work. The false power due to the so called wattless current pulsates in and out of the circuit without accomplishing any useful work.

An example of wattless current, showing that the power factor is zero is illustrated in fig. 2,123. Here the angle of lag is 90°, that is, the current is 90° behind the pressure.

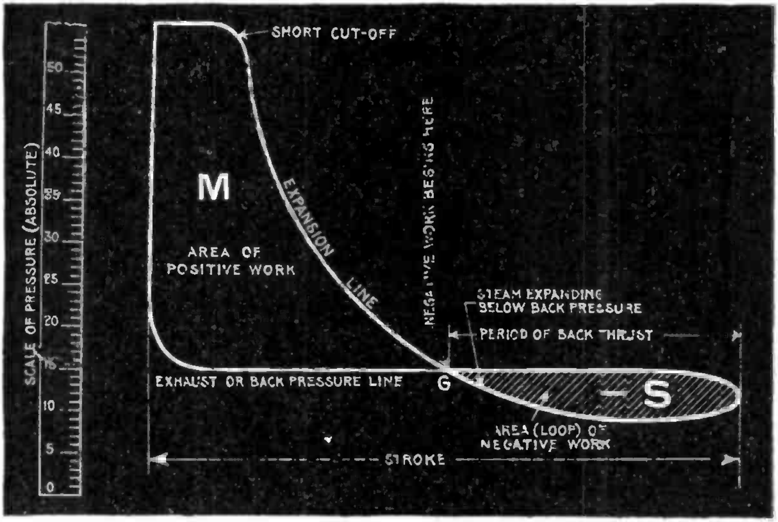


FIG. 2,124.—Steam engine analogy of power factor. The figure represents an indicator card of an engine in which the steam distribution is such that the steam is expanded below the back pressure line, that is below the pressure of the exhaust. This results in *negative work* which must be overcome by the *momentum* or *kinetic energy* previously stored in the fly wheel, and which is represented on the diagram by the shaded loop S. If the exhaust valve had opened at G, the amount of work done during the revolution would be represented by the area M, but continuing the expansion below the back pressure line, the work done is M − S. This latter case as compared with the first when expansion does not continue below the back pressure line gives an efficiency (power factor) of (M − S) ÷ M, the shaded area representing so much loss.

The power curve is constructed from the current and pressure curves, and, as shown in the diagram, it lies as much below the zero line as above, that is, the two plus power areas which occur during each period are equal to the two negative (shaded) power areas, showing that the circuit returns as much energy as is sent out. Hence, the total work done during each period is zero, indicating that although a current be flowing, this current is not capable of doing external work.

Ques. Is the condition as just described met with in practice?

Ans. No.

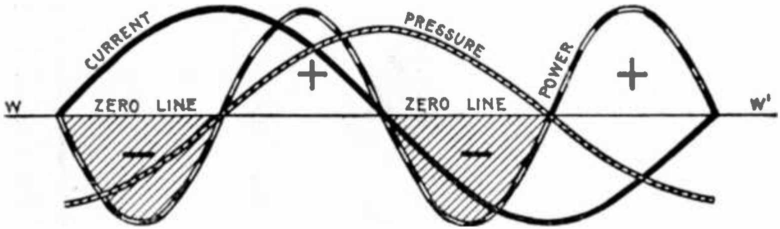


FIG. 2,122.—Power curve illustrating the so-called wattless current in which case the power factor is zero. By noting that the curve projects equally on each side of the zero line, the + power areas equal the negative power areas, hence the summation of these areas for the period is zero, that is, the two + areas minus the two shaded areas equal zero. It should be noted that the line of average power WW′, which is visible in the other figures here coincides with the zero line, and the average power then is zero, since the positive part above the zero line is equal to and offsets the negative (shaded) part below the line. This is the case of "wattless" current and (considering a circuit with resistance so small that it may be considered as zero) shows plainly the possibility of having full load current and voltage on a circuit yet delivering no power, the current simply surging to and fro without an actual transfer of power.

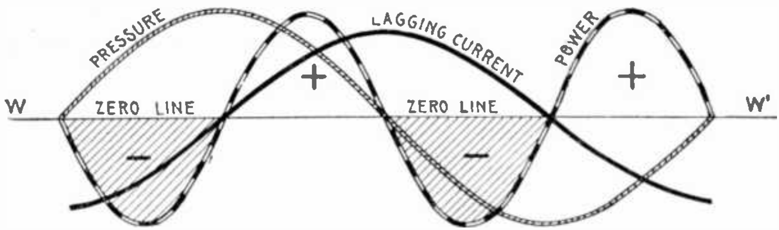


FIG. 2,123.—Example of wattless current showing that the power factor is zero when the phase difference between current and pressure is 90°. For zero power factor the current may *lead* 90° as in fig. 2,122, or *lag* 90° as here shown. Since the shaded or negative areas = the plus areas, the average power (indicated by WW′, which coincides with the zero line) is zero, that is the circuit is carrying current under pressure yet delivering no power, hence, the power factor is zero.

Ques. Why not?

Ans. The condition just described involves that the circuit have no resistance, all the load being reactance, but it is impossible to have a circuit without some resistance, though the resistance may be made very small in comparison to the reactance so that a close approach to wattless current is possible.

Ques. Give some examples where the phase difference is very nearly 90°.

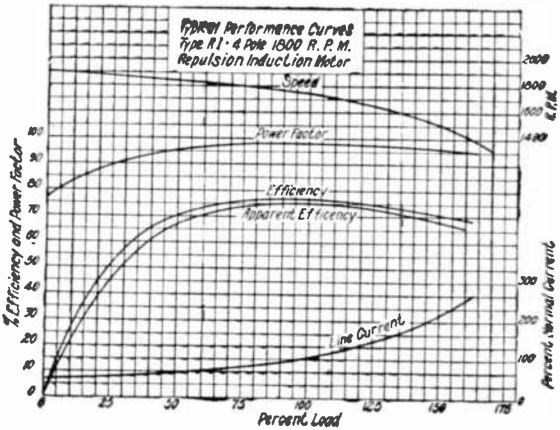


FIG. 2,124.—Performance curves of General Electric single phase repulsion induction motor.

Ans. If an alternator supply current to a circuit having a very small resistance and very large inductance, the current would lag nearly 90° behind the pressure.

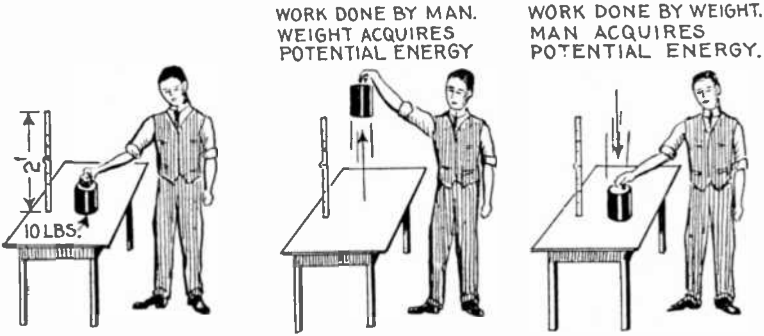
The primary current of a transformer working with its secondary on open circuit is a practical example of a current which represents very little energy.

Ques. When the phase difference between the current and pressure is 90°, why is the current called "wattless"?

Ans. Because the product of such a current multiplied by the pressure does not represent any watts *expended*.

A man lifting a weight, and then allowing it to descend the same distance to its initial position, as shown in figs. 2,125 to 2,127, presents a mechanical analogy of wattless current.

Let the movement of the weight represent the current and the weight the pressure. Then calling the weight 10 pounds (volts), and the distance two feet (amperes). The work done by the man (alternator) on the weight in lifting it is



FIGS. 2,125 to 2,127.—Mechanical analogy of wattless current. If a man lift a weight any distance, as from the position of fig. 2,125 to position of fig. 2,126, he does a certain amount of work on the weight giving it potential energy. When he lowers it to its original position, as in fig. 2,127, the weight loses the potential energy previously acquired, that is, it is given back to the man, the "system" (man and weight) having returned to its original condition as in fig. 2,125. During such a cycle, the work done by the man on the weight is equal to the work done by the weight on the man and no useful external work has been accomplished.

10 pounds × 2 feet = 20 foot pounds..................(1)
(10 volts × 2 amperes = 20 watts.)

The work done on the man by the weight in forcing his hand down as his muscles relax is

10 pounds × 2 feet = 20 foot pounds..................(2)
(10 volts × 2 amperes = 20 watts.)

From (1) and (2) it is seen that the *work done by the man on the weight is equal to the work done by the weight on the man*, hence no useful work has been accomplished; that is, the potential energy of the weight which it originally possessed has not been increased.

Why the Power Factor is Equal to Cosϕ.—In the preceding figures showing power curves for various phase relations between current and pressure, the curves show *the instantaneous values of the fluctuating power*, but what is of more importance is to determine *the average power developed.*

When the current is in phase with the pressure, it is a simple matter, because the power or

$$watts = amperes \times volts$$

that is, the product of the ammeter and volt meter readings will give the power. However, the condition of synchronism of current and pressure hardly ever exists in practice, there being more or less phase difference.

When the current is not in phase with the pressure, it is considered as made up of two components at right angles to each other.

1. *The active component*, in phase with the pressure;

2. *The wattless component*, at right angles to the pressure.

With phase difference between current and pressure the product of ammeter and volt meter readings does not give the true power, and in order to obtain the latter, the *active component* of the current in phase with the pressure must be considered, that is,

$$true\ power = volts \times active\ amperes \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The active component of the current is easily obtained graphically as in fig. 2,128.

With any convenient scale draw AB, equal to the current as given or read on the ammeter, and AC, equal to the pressure, making the angle ϕ between AB and AC, equal to the phase difference between the current and pressure.

From B, draw the line BD, perpendicular to AC, then BD, will be the wattless component, and AD (measured with the same scale as was used for AB) the active component of the current, or that component in phase with the pressure.

Hence from equation (1)

true power = AC × AD. . . . . (2)

Now in the right triangle ABD

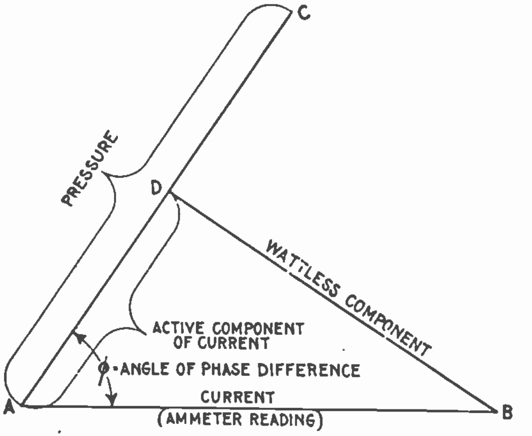
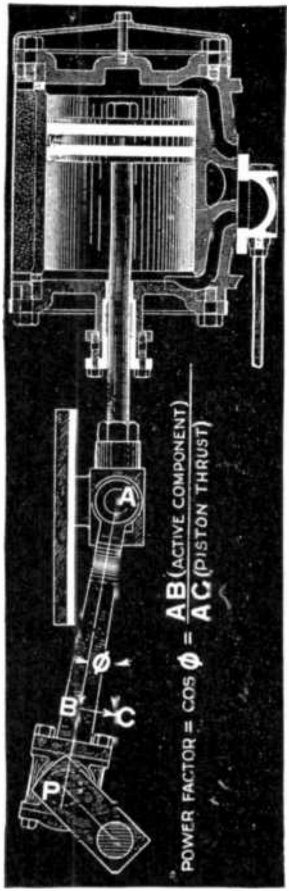


FIG. 2,128.—Method of obtaining the *active component* of the current; diagram illustrating why the power factor is equal to cos ϕ. If AB and AC, be respectively the given current and pressure, or readings of the ammeter and volt meter, and ϕ the angle of phase difference between current and pressure, then drawing from B, BD, perpendicular to AC, will give AD, the active component. Now, true power = AC × AD, but AD = AB cosϕ, hence true power = AC × AB cosϕ. Again, apparent power = AC × AB, and since true power = apparent power × power factor, the power factor = cosϕ.

$$\frac{AD}{AB} = \cos\phi$$

from which



$$AD = AB \cos\phi \dots\dots\dots (3)$$

Substituting this value of AD, in equation (2) gives

$$\text{true power} = AC \times AB \cos\phi \dots (4)$$

Now the power factor may be defined as *that quantity by which the apparent watts must be multiplied in order to give the true power.* That is

$$\textit{true power} = \textit{apparent watts} \times \textit{power factor} \dots\dots\dots\dots (5)$$

Comparing equations (4) and (5), AC×AB in (4) is equal to the apparent watts, hence, the power factor in (5) is equal to cosϕ. That is, *the power factor is numerically equal to the cosine of the angle of phase difference between current and pressure.*

FIG. 2,129.—Angularity of the connecting rod analogy of power factor. Pressure due to steam acting on the piston is applied to the wrist pin in the axial direction AC. Let distance AC, represent this pressure. Draw CB, perpendicular to connecting rod AP. Then will AC, represent the *apparent* pressure applied to P, the crank pin; AB, the active component or actual pressure applied to P, and BC, the no energy component. Power factor = AB ÷ AC, = Cosϕ. *Example.*—If 1,000 lbs. pressure be applied by piston and AB ÷ AC = .9, then the actual pressure applied at P = 1,000 × .9 = 900 lbs.

Example 1.—An alternator supplies a current of 200 amperes at a pressure of 1,000 volts. If the phase difference between the current and pressure be 30°, what is the true power developed?

In fig. 2,130, draw AB, to scale, equal to 200 amperes, and draw AC, of indefinite length making an angle of 30° with AB. From B, draw BD, perpendicular to AC, which gives AD, the active component, and which measured with the same scale as was used in laying off AB, measures 173:2 amperes. The true power developed then is

$$\text{true watts} = 173.2 \times 1{,}000 = 173.2 \text{ kw.}$$

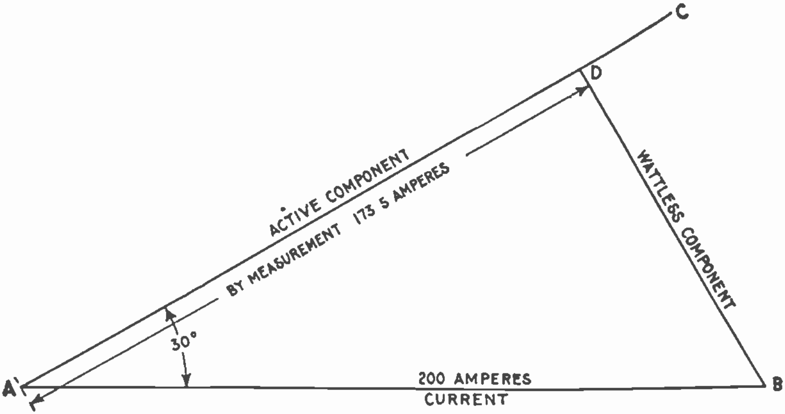


FIG. 2,130.—Diagram for obtaining the active component of the current in a circuit having a current of 200 amperes and angle of lag of 30°.

The true power may be calculated thus:

From a cosine table cos 30° = .866, hence

$$\text{true watts} = 200 \times 1{,}000 \times .866 = 173.2 \text{ kw.}$$

Example 2.—If in an alternating current circuit, the volt meter and ammeter readings be 110 and 20 and the angle of lag 45°, what is the apparent power and true power?

The apparent power is simply the product of the current and pressure readings or

$$\text{apparent power} = 20 \times 110 = 2{,}200 \text{ watts}$$

The true power is the product of the apparent power multiplied by the cosine of the angle of lag. Cos 45° = .707, hence true power = 2,200 × .707 = 1,555.4 watts.

Ques. Does the power factor apply to capacity reactance in the same way as to inductance reactance?

Ans. Yes.

The angles of lag and of lead, are from the practical standpoint, treated as if they lay in the first quadrant of the circle. Even the negative sign of the $\tan\phi$ when it occurs is simply used to determine whether the

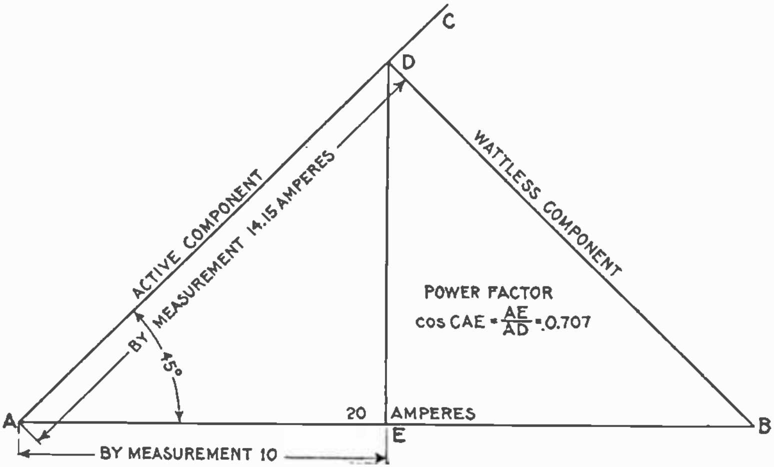


FIG. 2,131.—Diagram for obtaining the power factor for example 2. With convenient scale, lay off AB = 20 amperes. From A, draw AC, at 45° to AB, and from B, draw BD, perpendicular to AC. Then, the power factor which is equal to cosine of angle of lag, = AD ÷ AB = (by measurement) 14.15 ÷ 20 = .707.

angle be one of lag or of lead, but in finding the value of the angle from a table it is treated as a positive quantity.

Ques. In introducing capacity into a circuit to increase the power factor what should be considered?

Ans. The cost and upkeep of the added apparatus as well as the power lost in same.

Ques. How is power lost in a condenser?

Ans. The loss is principally due to a phenomenon known as *dielectric hysteresis*, which is somewhat analogous to magnetic hysteresis.

The rapidly alternating charges in a condenser placed in an alternating circuit may be said to cause alternating polarization of the dielectric, and consequent heating and loss of energy.

Ques. When is inductance introduced into a circuit to increase the power factor?

Ans. When the phase difference is due to an excess of capacity.

Example 1.—A circuit having a resistance of 3 ohms, and a resultant reactance of 4 ohms, is connected to a 100 volt line. What is: 1, the impedance, 2, the current, 3, the apparent power, 4, the angle of lag, 5, the power factor, and 6, the true power?

1. *The impedance of the circuit.*
   $Z = \sqrt{3^2+4^4} = 5$ ohms.

2. *The current.*
   current = volts ÷ impedance = 100 ÷ 5 = 20 amperes.

3. *The apparent power.*
   apparent power = volts × amperes = 100 × 20 = 2,000 watts.

4. *The tangent of the angle of lag.*
   $\tan \phi$ = reactance ÷ resistance = 4 ÷ 3 = 1.33. From table of natural tangents (page 921) $\phi = 53°$.

5. *The power factor.*
   The power factor is equal to the cosine of the angle of lag, that is, power factor = cos 53° = .602 (from table).

6. *The true power.*
   The true power is equal to the apparent watts multiplied by the power factor, or

$$\text{true power} = \text{volts} \times \text{amperes} \times \cos \phi$$

$$= 100 \times 20 \times .602 = 1{,}204 \text{ watts.}$$

Ques. Prove that the power factor is unity when there is no resultant reactance in a circuit.

Ans. When there is no reactance, tanϕ which is equal to reactance÷resistance becomes $0 \div R = 0$. The angleϕ (the

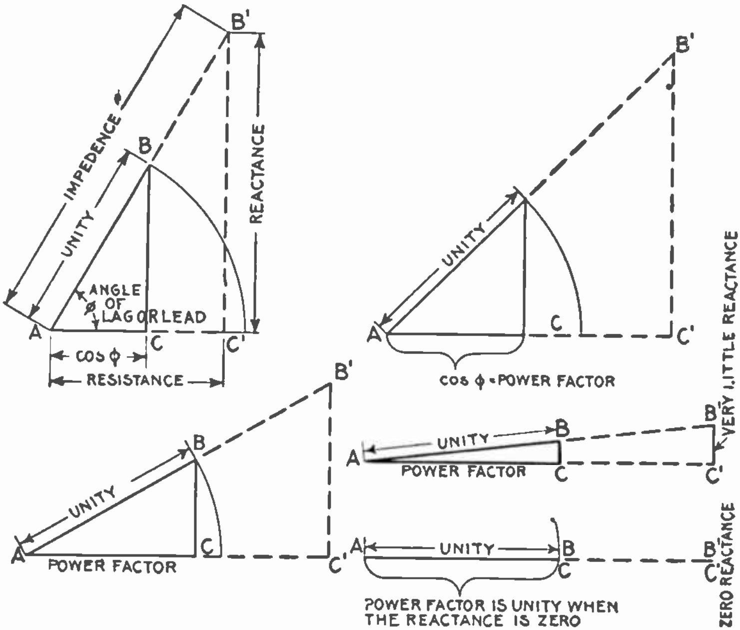


FIG. 2,132 to 2,136.—Diagrams illustrating why the power factor is unity or one when there is no resultant reactance in the circuit, that is, when the circuit is resonant or has only resistance. The power factor is equal to the cosine of the angle of lag (or lead). In the figures this angle is BAC, or ϕ, and the value of the *natural cosine* AC, gives the power factor. By inspection of the figures, it is evident that decreasing the reactance decreases the angle ϕ and increases cos ϕ or the power factor. The circular arc in each figure being at unity distance from the center A, the power factor with decreasing reactance evidently approaches unity as its limit, this limit being shown in fig. 2,136 where the reactance $B'C' = O$.

phase difference angle) whose tangent is 0, is the angle of 0 degrees. Hence, the power factor which is equal to $\cos\phi = \cos 0° = 1$.

Ques. What is the usual value of the power factor in practice?

Ans. Slightly less than one.

Ques. Why is it desirable to keep the power factor near unity?

Ans. Because with a low power factor, while the alternator

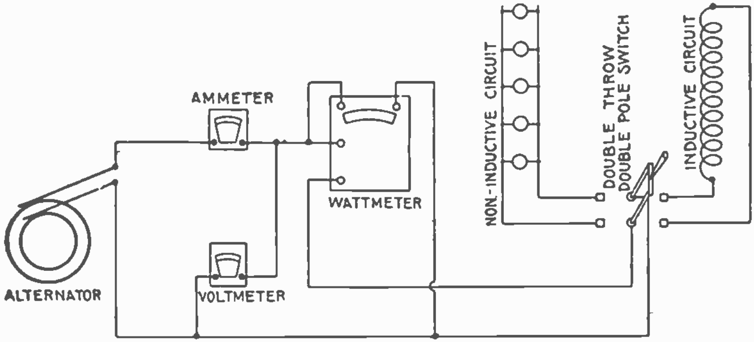


FIG. 2,137.—Diagram illustrating power factor test, when on non-inductive and inductive circuits. The instruments are connected as shown and by means of the double throw switch can be put on either the non-inductive or inductive circuit. First turn switch to left so that current passes through the lamps; for illustration, the following readings are assumed: ammeter 10, volt meter 110, and watt meter 1,100. The power factor then is watt meter reading ÷ volts × amperes = 1,100 actual watts ÷ 1,100 apparent watts = 1, that is, on non-inductive circuit the power factor is unity. Now throwing the switch to the right connecting instruments with the inductive circuits, then for illustration the following readings may be assumed: ammeter 8, volt meter 110, and watt meter 684. Now, as before, power factor = watt meter reading ÷ volts × amperes = 684 ÷ (8 × 110) = 684 ÷ 880 = .78.

may be carrying its full load and operating at a moderate temperature, the consumer is paying only for the actual watts which are sent over the line to him.

For instance, if a large alternator supplying 1,000 kilowatts at 6,600 volts in a town where a number of induction motors are used on the line be operating with a power factor of say .625 during a great portion of the time, the switchboard instruments connected to the alternator will give the following readings:

Volt meter 6,600 volts; ammeter 242.4 amperes; power factor meter .625.

The apparent watts would equal 1,600,000 watts or 1,600 kilowatts, which, if multiplied by the power factor .625 would give 100,000,000 watts or 1,000 kilowatts which is the actual watts supplied. The alternator and line must carry 242.4 amperes instead of 151 amperes and the difference 242.4 − 151 = 91.4 amperes represents a *wattless current* flowing in the circuit which causes useless heating of the alternator.

The mechanical power which is required to drive the alternator is equivalent to the actual watts produced, since that portion of the current which lags, is out of phase with the pressure and therefore requires no energy.

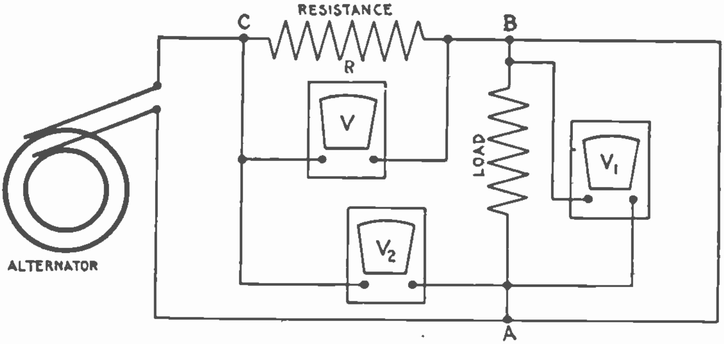


FIG. 2,138.—Ayrton and Sumpner method of alternating current power measurement. Three volt meters are required, and accordingly the method is sometimes called the three volt meter method. It is a good method where the voltage can be regulated to suit the load. In the figure, let the non-inductive resistance R, be placed in series with the load AB. Measure the following voltages: V, across the terminals of R, V_1, across the load AB, and V_2, across both, that is, from A, to C. Then, true watts = $(V_2^2 - V_1^2 - V^2) \div 2R$. The best conditions are when $V = V_1$, and, if R = ½ ohm, then $W = V_2^2 - V_1^2 - V^2$.

Ques. How are alternators rated by manufacturers in order to avoid disputes?

Ans. They usually rate their alternators as producing so many kilovolt amperes instead of kilowatts.

Ques. What is a kilovolt ampere (kva)?

Ans. A unit of apparent power in an alternating current circuit which is equal to one kilowatt when the power factor is equal to one.

The machine mentioned on page 1,522 would be designed to carry 151 amperes without overheating and also carry slight overloads for short periods. It would be rated as 6.6 kilovolts and 151 amperes which would equal approximately 1,000 kilowatts when the power factor is 1 or unity, and it should operate without undue heating. Now the lower the power factor becomes, the greater the heating trouble will be in trying to produce the 1,000 actual kilowatts.

Ques. How can the power factor be kept high?

Ans. By carefully designing the motors and other apparatus and even making changes in the field current of motors which are already installed.

Ques. How is the power factor determined in station operation?

Ans. Not by calculation, but by reading a meter which forms one of the switchboard instruments.

Ques. When is the power factor meter of importance in station operation, and why?

Ans. When rotary converters are used on *a.c.* lines for supplying direct currents and the sub-station operators are kept busy adjusting the field rheostat of the rotary to maintain a high power factor and prevent overheating of the alternators during the time of day when there is the maximum demand for current or the peak of the load.

Example.—An alternator delivers current at 800 volts pressure at a frequency of 60, to a circuit of which the resistance is 75 ohms and .25 henry.

Determine: *a*, the value of the current; *b*, angle of lag; *c*, apparent watts; *d*, power factor; *e*. true power.

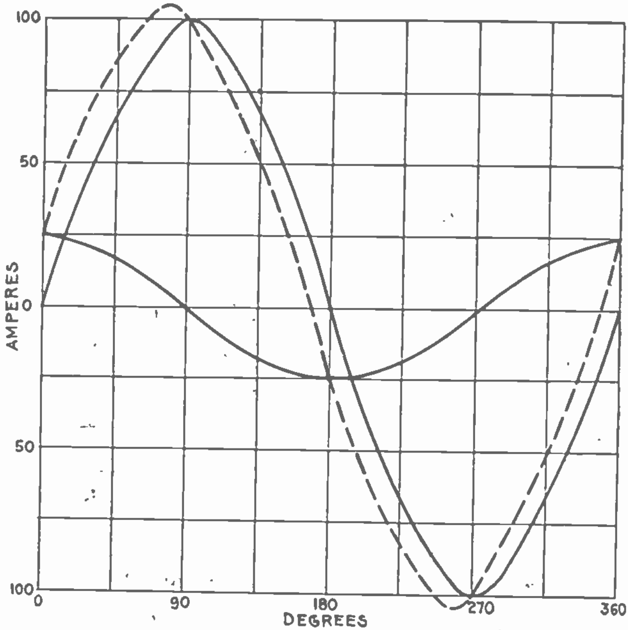


FIG. 2,139.—Curves illustrating *power factor*. In a circuit having no capacity or inductance, the power is given by the product of the respective readings of the volt meter and ammeter, as in the case of a direct current. In the case of a circuit having capacity or inductance, this product is higher than the true value as found by a watt meter, and is known as the *apparent watts*. The ratio *true watts ÷ apparent watts* is known as the power factor. The current flowing in an inductive circuit, such as the primary of a transformer, is really made up of two components, as already explained, one of which (the load or active component) is in phase with the pressure, while the other the magnetizing component, is at right angles to it, that is, it attains its crest value when the other is at zero, and vice versa. To illustrate, take a complete cycle divided into 360 degrees and lay out on it the current required to correspond to a given load on the secondary of a transformer, say a crest value of 100 amperes, and at right angles to this lay out the current required for exciting the magnetic circuit of the transformer, giving A, merely for purpose of illustration, a crest value of 25 amperes. Combining these curves, the dotted curve in the figure is obtained and which represents the resultant current that would be indicated by an ammeter placed in the primary circuit of the transformer. It will be noted that this current attains its maximum at a point 14° 2′ later than the load current, giving the angle of lag. Multiplying the apparent watts by the cosine of the angle of lag gives the true watts. Now assuming the diagram to show the full load condition of the transformer, the angle of lag being 14° 2′, the power factor at full load is .97 (.97 being the value of the natural cosine of 14° 2′ as obtained from a table, of natural cosines). With no external load on the transformer, the load component of the current is that necessary to make up the core losses.

a. Value of current

$$\text{current} = \frac{\text{pressure}}{\text{impedance}} = \frac{E}{\sqrt{R^2+(2\pi f L)^2}}$$

$$= \frac{800}{\sqrt{75^2+(2\times3.1416\times60\times.25)^2}} = 6.7 \text{ amperes}$$

b. The angle of lag

$$\tan\phi = \frac{\text{reactance}}{\text{resistance}} = \frac{2\pi f L}{R} = \frac{2\times3.1416\times60\times.25}{75} = 1.25$$

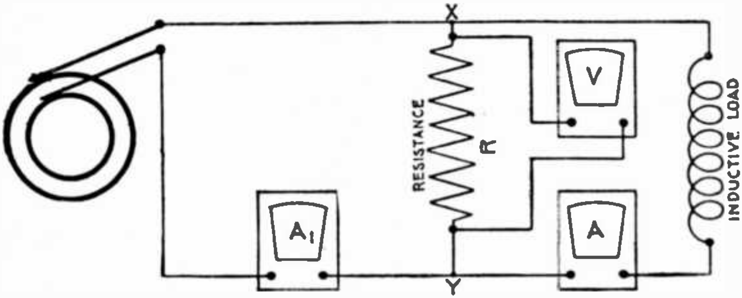


FIG. 2,140.—Fleming's combined volt meter and ammeter method of measuring power in alternating current circuits. It is quite accurate and enables instruments in use to be checked. In the figure, R, is a non-inductive resistance connected in shunt to the inductive load. The volt meter V, measures the pressure across the resistance XY. A and A, are ammeters connected as shown. Then, true watts $= \left(A_1^2 - A - \left(\frac{V}{R}\right)^2\right)\times\frac{R}{2}$. If the volt meter V, take an appreciable amount of current, it may be tested as follows: disconnect R and V, at Y, and see that A and A_1, are alike; then connect R and V, at Y, again, and disconnect the load. A_1, will equal current taken by R and V, in parallel.

ϕ = angle of lag = 1.25 = 51° 15′ (interpolating from table, page 921).

c. The apparent power

apparent power = volts × amperes = 800 × 6.7 = 5,360 watts
= 5.36 kva.

d. The power factor

power factor = cosine of the angle of lag
= cos 51° 15′ = .626.

e. The true power

true power = apparent power × power factor
= 5,360 × .626 = 3,355 watts.

Poor Power Factor an Executive Problem.—*A.c.* motors require current for field magnetization. This magnetizing current is taken from the source of current supply and flows through the motor field and back to the mains without doing any useful work, and serves only to magnetize the motor. The power current, on the other hand, is the flow of electricity whose energy is converted by the motor into useful mechanical

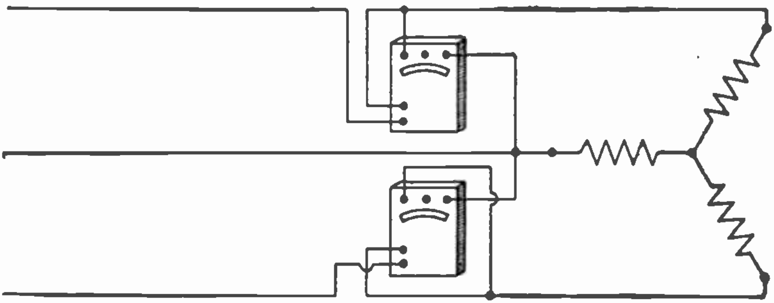


FIG. 2,141.—Watt meter method of three phase power measurement. Two watt meters are required in unbalanced systems as shown in the illustration. The total power transmitted is then the algebraic sum of the readings of the two watt meters. If the power factor be greater than .5, the power is the arithmetical sum, and if it be less than .5, the power is the arithmetical difference of the readings.

work. An *a.c.* motor, therefore, requires a total current which is composed of magnetizing and power current.

Power factor, the ratio between the power current and the total current supplied to the motor, is a measure of the utilization of the current furnished.

It is an indication of the proportion of the electricity that is converted into useful work. The balance simply serves to magnetize the motor. Power factor less than unity has been recognized and understood by engineers to be a problem influencing economy since the first use was made of alternating current machinery. Today, however, low power factor has become an executive and managerial problem, for correction of low power means greater and better production, reduced power costs and increased profits.

Low Power Factor Causes Many Avoidable Wastes.—The effects of low power factor are felt in all industries and it results in many avoidable manufacturing wastes of which the following are some of the principal examples:

1. Relatively large and costly electrical equipment, including alternators, cables, switches and transformers, the dimensions of which are governed by the total current rather than the power current.

2. Reduced efficiency for the whole of the electrical equipment because the copper losses for a given power load are inversely proportional to the square of the power factor.

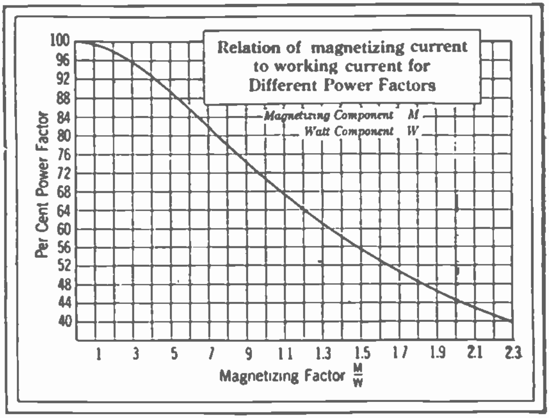
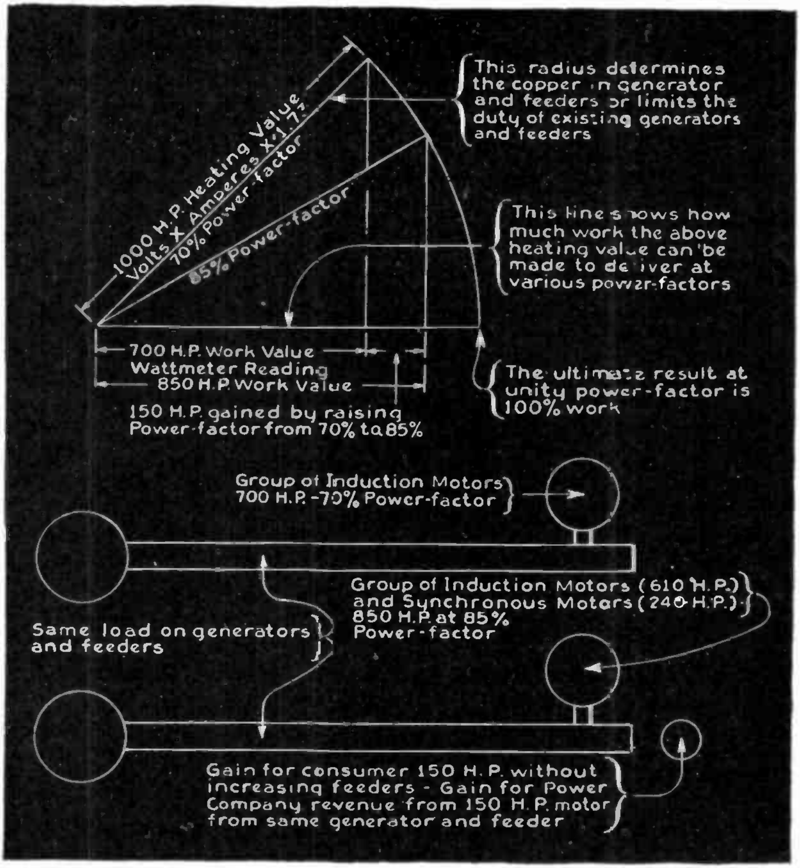


FIG. 2,142.—Power factor curve. By aid of this curve the magnetizing *kva.* can be determined for any power factor. *For instance,* a line with 60 per cent. power factor and a load of 150 *kw.* requires 150 multiplied by 1.3 = 195 magnetizing *kva.*

3. Poor voltage regulation for the whole system. Low power factor creates a heavy voltage drop in inside factory wiring as well as further reducing the voltage by its influence on the entire electric distributing system from the power house to the factory. This reduction in voltage (poor regulation) results in many evil effects such as overheating of motors, decrease in their maximum horse power capacity, decrease in their starting torque, unsteady speed and shortening of their useful life.

4. A higher cost for power current because the initial cost of the electrical system as a whole is relatively high per unit of power current supplied.

The effects of poor regulation caused by low power factor will be noticeable in the manufactured product of any plant because variation of voltage means fluctuation in motor speed.



FIGS. 2,143 to 2,145.—Typical power factor diagram showing gain by raising the power factor; fig. 2,145 shows benefits to consumer and power company on the basis shown in fig. 2,144.

This fluctuation is sufficient in some cases to cause a distinct falling off in production. In other cases, however, a fluctuation in motor speed will influence the uniformity of machine made products while not sufficient to reduce production. Poor regulation also means poor lighting which always results when the voltage fluctuates, so that here again low power factor, by causing poor industrial lighting, reduces production and the quality of machine manufactured products.

Low power factor by increasing the current required by motors increases the energy losses in the distribution system.

These wiring losses due to low power factor in some cases become extremely large when compared with the total energy required by the plant and in many cases the plant wiring is so taxed by the heavy current that it is too small to give satisfactory service.

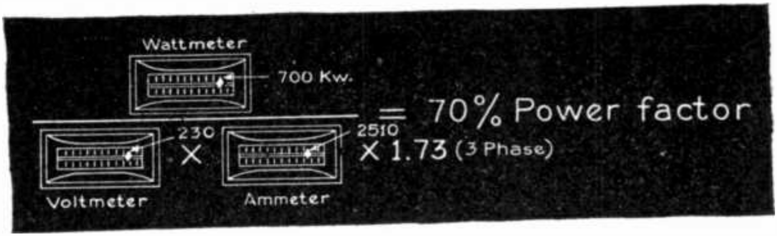


FIG. 2,146.—Meter reading on three phase circuit 70% power factor.

An energy loss of 10 per cent may be easily reached with a voltage drop of three per cent if the power factor be not corrected.

An 80 per cent power factor results in about a five per cent energy loss in the wiring system when the measured voltage drop is about three per cent as the following calculation will show.

It is sometimes considered that if the voltage drop between the source of supply and the motor be three per cent that the energy loss be also three per cent. The fact is, however. that the energy loss is inversely proportional to the square of the power factor so that if the voltage drop be three per cent the energy loss at different power factors will be as follows:

For an 80% power factor

$$3\% \div .64 = 4.7\%$$

For a 55% power factor
$3\% \div .3 = 10\%$

Low Power Factor Increases Operating Cost.—Manufacturers who operate their own generating plants suffer a large investment loss through low power factor. Excess capacity of alternators, lines, transformers, feeders, and switching equipment is necessary to take care of magnetizing current.

Electrical investment cost varies inversely (approximately) as the power factor so that a system designed for 70 per cent power factor costs about 40 per cent more than one designed for unity power factor.

In the case of a manufacturer who purchases current his power rate must contain all of the generating cost as well as a profit on these costs so that if the power factor of the generating system be low, the manufacturer in his power rate pays the interest charges upon the extra investment caused by low power factor.

TEST QUESTIONS

1. *Define the term power factor.*
2. *Give two marine analogies illustrating power factor.*
3. *What is the difference between the true power and the apparent power?*
4. *What is usually meant by power factor?*
5. *Upon what does the power factor depend?*
6. *How does the power factor vary in value?*
7. *What is the effect of lag or lead of the current on the power factor?*
8. *Give method of obtaining the power curve.*
9. *Under what condition is the power factor unity?*

10. *What should be noticed about the power curve?*
11. *Can the power factor be less than unity if the current and pressure be in phase?*
12. *What is the effect of lag and lead on power factor?*
13. *Can the power factor be zero?*
14. *What does the term wattless current mean?*
15. *Give steam engine analogy of power factor.*
16. *Give some examples where the phase difference is very nearly 90°.*
17. *Why is the power factor equal to cosϕ?*
18. *Does the power factor apply to capacity reactance in the same way as to inductance reactance?*
19. *How is power lost in a condenser?*
20. *When is inductance introduced into a circuit to increase the power factor?*
21. *Prove that the power factor is unity when there is no resultant reactance in a circuit.*
22. *What is the usual value of the power factor in practice?*
23. *Why is it desirable to keep the power factor near unity?*
24. *How are alternators rated by manufacturers in order to avoid disputes?*
25. *What is a kilovolt ampere (kva)?*
26. *How can the power factor be kept high?*
27. *How is the power factor determined in station operation?*

CHAPTER 50

Alternators

Use of Alternators.*—The great increase in the application of electricity for supplying power and for lighting purposes in industry, commerce, and in the home, is due chiefly to the economy of distribution of alternating current.

Direct current may be used to advantage in densely populated districts, but where the load is scattered, it requires, on account of its low voltage, too great an investment in distributing lines. In such cases the alternator is used to advantage, for while commutators can be built for collecting direct current up to 1,000 volts, alternators can be built up to 12,000 volts or more, and this voltage increased, by step up transformers of high economy, up to 100,000 volts or more. Since the copper cost is inversely as the square of the voltage, the great advantage of alternating current systems is clearly apparent.

The use of alternating current thus permits a large amount of energy to be economically distributed over a wide area from a single station, not only reducing the cost of the wiring, but securing greater economy by the use of one large station, instead of several small stations.

The higher voltages generated by alternators enables the transmission of electrical energy to vastly greater distances than possible by a direct current system, so that the energy from many waterfalls that otherwise would go to waste may be utilized.

Classes of Alternator.—There are various ways of classifying alternators. They may be divided into groups, according to

*NOTE.—The author objects to the ridiculous terms *alternating current generator* for *alternator* and *direct current generator* for *dynamo*. Why use three words in place of one?

1, the nature of the current produced; 2, type of drive; 3, method of construction; 4, field excitation; 5, service requirements, etc.

From these several points of view, alternators then may be classified:

1. With respect to the current, as:

   a. Single phase;
   b. Polyphase.

2. With respect to the type of drive, as:

   a. Belt or chain driven;
   b. Direct connected.

3. With respect to construction, as:

   a. Revolving armature;
   b. Revolving field;
   c. Inductor.
   Homopolar and heteropolar.

4. With respect to mode of field excitation, as:

   a. Self-exciting;
   b. Separately excited;
   Exciter direct connected, or gear driven.
   c. Compositely excited.

5. With respect to service requirements, as:

   a. Slow speed;
   b. Fly wheel;
   c. High speed;
   d. Water wheel type;
   e. Turbine driven.

Single Phase Alternators.—As a general rule, when alternators are employed for lighting circuits, the single phase machines are preferable, as they are simpler in construction and do not generate the unbalancing voltages often occurring in polyphase work.

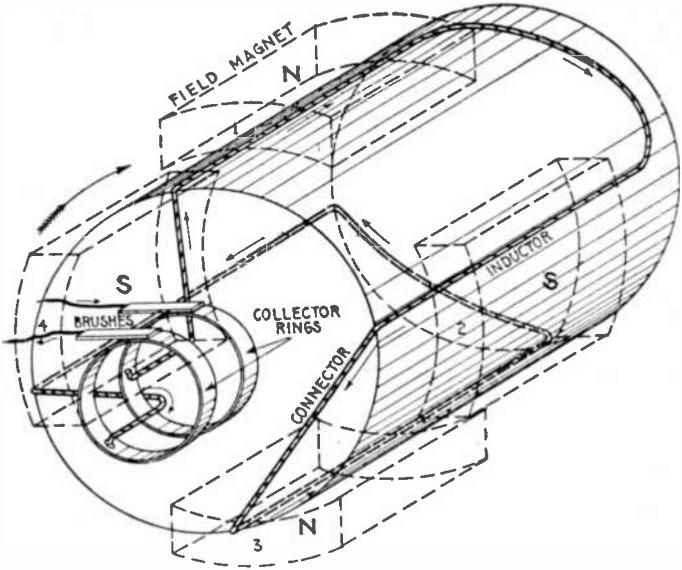


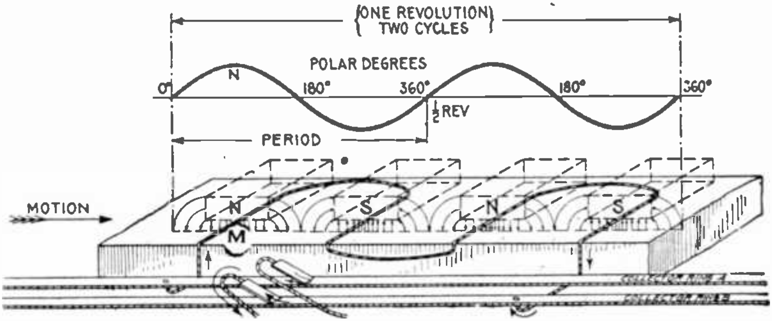
FIG. 2,147.—Elementary four-pole single phase alternator. It has four "inductors" whose pitch is the same as the pole pitch. They are connected in series and terminate at the two collector rings as shown. The poles being alternate N and S, it is evident that there will be two cycles of the current per revolution of the armature. For any number of poles, then, the number of cycles equals the number of poles divided by two. Applying Fleming's rule for induced currents, the direction of the current induced in the inductors is easily found as indicated by the arrows. The field magnets are excited by coils supplied with direct current, usually furnished from an external source; for simplicity this is not shown. The magnets may be considered as of the permanent type.

Ques. What are the essential features of a single phase alternator?

Ans. Fig. 2,147 shows an elementary single phase alternator.

It consists of an armature, with single phase winding, field magnets, and two collector rings and brushes through which the current generated in the armature passes to the external circuit.

Ques. In what respect do commercial machines differ mostly from the elementary alternator shown in fig. 2,147, and why?



FIGS. 2,148 and 2,149.—Developed view of elementary single phase four pole alternator and sine curve showing the alternating current or pressure generated during one revolution. The armature is here shown as a flat surface upon which a complete view of the winding is seen. If M, be any position of an inductor, by projecting up to the curve gives N, the corresponding value of the current or pressure. Magnetic lines are shown at the poles representing a a field decreasing in intensity from a maximum at the center to zero at points half way between the poles, this being the field condition corresponding to the sine form of wave. In actual machines the variation from the sine curve is considerable in some alternators. See figs. 1,968 and 1,969.

Ans. They have a large number of poles and inductors in order to obtain the desired frequency, without excessive speed, and electro-magnets instead of permanent magnets.

Ques. In actual machines, why must the magnet cores be spaced out around the armature with considerable distance between them?

Ans. In order to get the necessary field winding on the cores, and also to prevent undue magnetic leakage taking place, laterally from one limb to the next of opposite sign.

Ques. Is there any gain in making the width of the armature coils any greater than the pole pitch, and why?

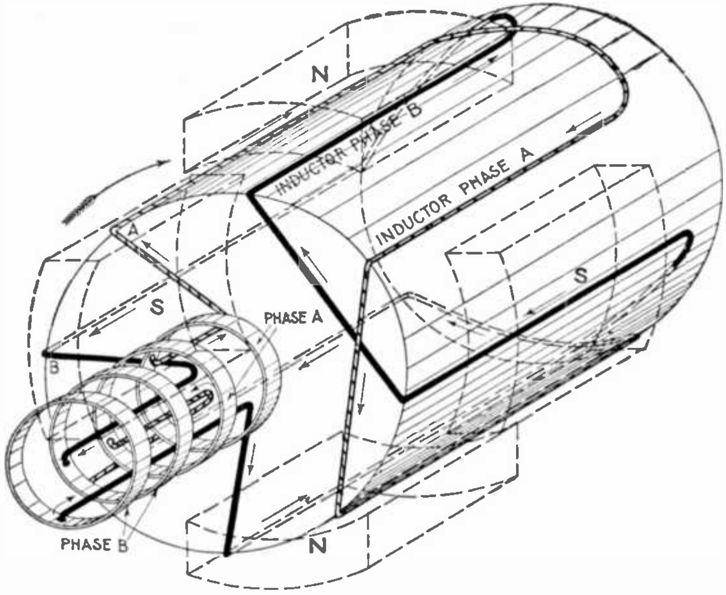
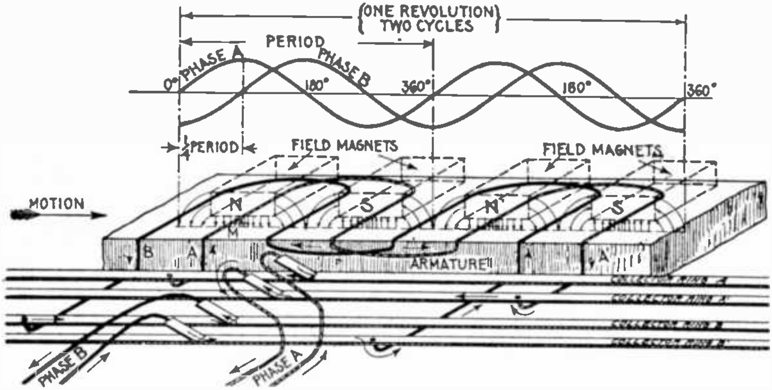


FIG. 2,150.—Elementary four pole two phase alternator. The winding consists of one inductor per phase per pole, that is, four inductors per phase, the inductors of each phase being connected in series by the "connectors" and terminating at the collector rings. This arrangement requires four collector rings, giving two independent circuits. The pitch of the inductors of each phase is equal to the pole pitch, and the phase difference is equal to one-half the pole pitch, that is, phase B, winding begins at B, a point half-way between inductors A and A′, of phase A, winding. Hence when the current or pressure in phase A, is at a maximum, in the ideal case, when inductor A, for instance is under the center of a pole, the current or pressure in B, is zero, because B, is then half-way between the poles.

Ans. No, because any additional width will not produce more voltage, but on the contrary will increase the resistance and inductance of the armature.

Polyphase Alternators.—A multiphase or polyphase alternator is one which delivers two or more alternating currents differing in phase by a definite amount.

For example, if two armatures of the same number of turns each be connected to a shaft at 90 degrees from each other and revolved in a bipolar field, and each terminal be connected to a collector ring, two sep-



FIGS. 2,151 and 2,152.—Developed view of elementary two phase four pole alternator and sine curves, showing the alternating current or pressure generated during one revolution of the armature. The complete winding for the two phases is here visible, the field magnets being represented as transparent so that all of the inductors may be seen. By applying Fleming's rule, as the inductors progress under the poles, the directions and reversals of current are easily determined, as indicated by the sine curves. It will be seen from the curves that four poles give two cycles per revolution. Inductors A and B, are lettered to correspond with fig. 2,150, with which they should be compared.

arate alternating currents, differing in phase by 90 degrees, will be delivered to the external circuit. Thus a two phase alternator will deliver two currents differing in phase by one-quarter of a cycle, and similarly a three phase alternator (the three armatures of which are set 120 degrees from each other) will deliver three currents differing in phase by one-third of a cycle.

In practice, instead of separate armatures for each phase, the several windings are all placed on one armature and in such sequence that the currents are generated with the desired phase difference between them as shown in the elementary diagrams 2,150 to 2,152 for two phase current, and figs. 2,153 to 2,155 for three phase current.

Ques. What uses are made of two and three phase current?

Ans. They are employed rather for power purposes than for lighting, but such systems are often installed for both services.

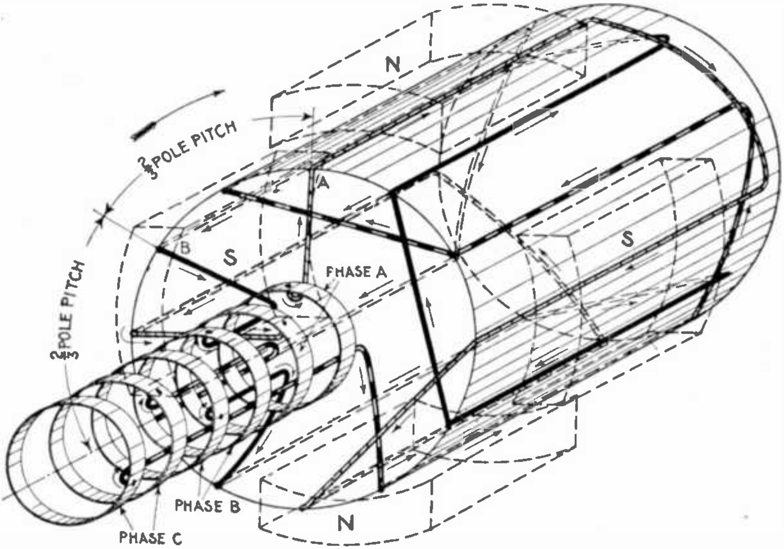
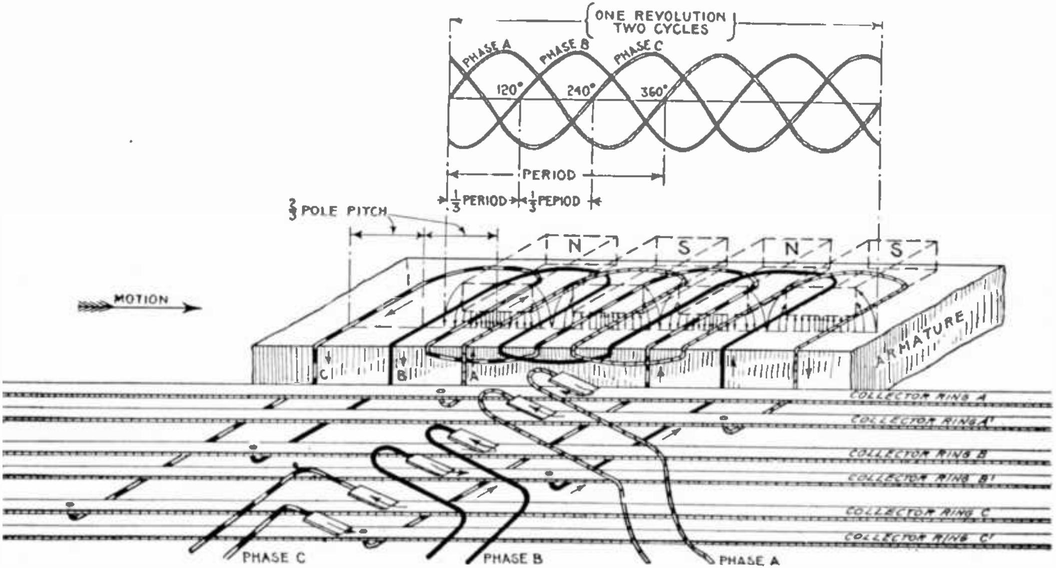


FIG. 2,153.—Elementary four pole three phase alternator. There are three sets of inductors, each set connected in series and spaced on the drum with respect to each other two-thirds pole pitch apart. As shown, six collector rings are used, but on actual three phase machines only three rings are employed, as previously explained. The inductors have distinctive coverings for the different phases. The arrows indicate the direction in which the induced pressures tend to cause currents.

Ques. How are they employed in each case?

Ans. For lighting purposes the phases are isolated in separate circuits, that is, each is used as a single phase current. For driving motors the circuits are combined.

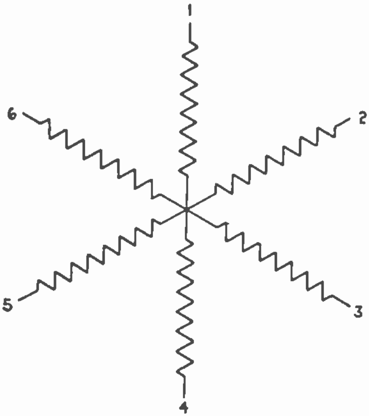


FIGS. 2,154 and 2,155.—Elementary four pole three phase alternator and sine curves showing current or pressure conditions for one revolution. Six collector rings are shown giving three independent circuits. The pitch of the inductors for each phase is the same as the pole pitch, and the phase difference is equal to two-thirds of the pole pitch, giving the sequence of current or pressure waves as indicated by the sine curves. The waves follow each other at ⅓ period, that is, the phase difference is 120 degrees. Inductors A, B and C, the beginning of each phase winding, are lettered to correspond with fig. 2,153, with which they should be compared.

Ques. Why are they combined for power purposes?

Ans. On account of the difficulty encountered in starting a motor with single phase current.

Ferarris, of Italy, in 1888 discovered the important principle of the



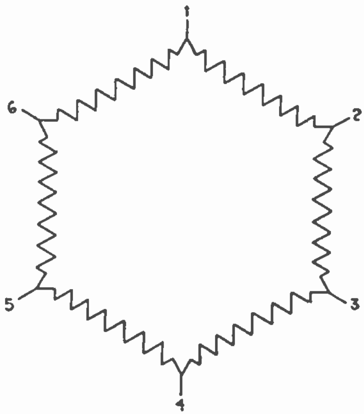


Fig. 2,156.—Diagram of six phase winding with star grouping, being equivalent to a three phase winding in which the three phases are disconnected from each other and their middle points united at a common junction.

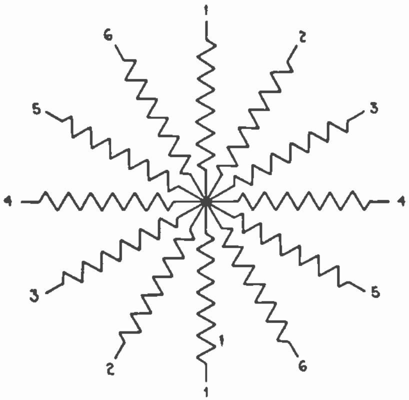
Fig. 2,157.—Diagram of six phase winding with mesh grouping.

production of a rotating magnetic field by means of two or more alternating currents displaced in phase from one another, and he thus made possible by means of the induction motor, the use of polyphase currents for power purposes.

Ques. What is the difficulty encountered in starting a motor with single phase current?

Ans. A single phase current requires either a synchronous motor to develop mechanical power from it, or a specially constructed motor of dual type, the idea of which is to provide a method of getting rotation by foreign means and then to throw in the single phase current for power.

Six Phase and Twelve Phase Windings.—These are required for the operation of rotary converters. The phase difference in a six phase winding is 60 degrees and in a twelve phase winding 30 degrees.



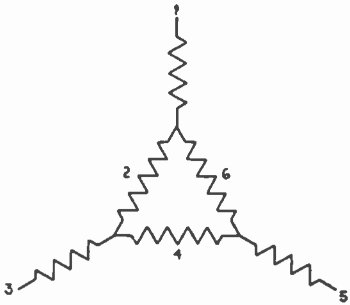


FIG. 2,158.—Diagram of twelve phase winding with star grouping.

FIG. 2,159.—Diagram of six phase winding consisting of combination of mesh and star grouping.

A six phase winding can be made out of a three phase winding by disconnecting the three phases from each other, uniting their middle points at a common junction, as shown by diagram fig. 2,156. This will give a star grouping with six terminals.

In the case of a mesh grouping, each of the three phases must be cut into two parts and then reconnected as shown in fig. 2,157.

As the phase difference of a twelve phase winding is one-half that of a six phase winding, the twelve phases may be regarded as a star grouping of six pairs crossed at the middle point of each pair as shown in fig. 2,158, or in mesh grouping for converters they may be arranged as a twelve pointed polygon. They may also be grouped as a combination of mesh and star as shown in fig. 2,159, which, however, is not of general interest.

Belt or Chain Driven Alternators.—The mode in which power is transmitted to an alternator for the generation of current is governed chiefly by conditions met with where the machine is to be installed.

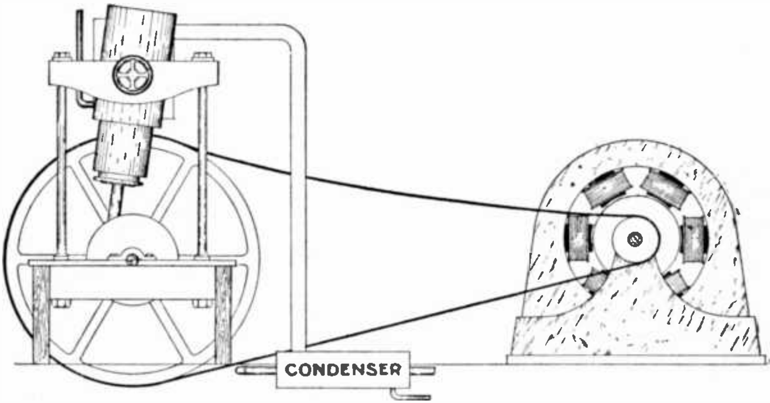


FIG. 2,160.—Belt-driven alternator. By use of a belt, any desired speed ratio is obtained, enabling the use of a high speed alternator which, being smaller than one of slow speed, is cheaper. It affords a means of drive for line shaft and has other advantages, but requires considerable space and is not a "positive" drive. Belting exerts a side pull which results in friction and wear of the bearings. The illustration shows alternator driven by Graham special trunk piston transfer expansion steam jacketted oscillating engine.

In many small power stations and isolated plants the use of a belt drive is unavoidable. In some cases the prime mover is already installed and cannot be conveniently arranged for direct connection, in others the advantage to be gained by an increase in speed more than compensates for the loss involved in belt transmission.

There are many places where belted machines may be used advantageously and economically. They are easily connected to an existing source of power, as, for instance, a line shaft used for driving other machinery, and for comparatively small installations they are lower in first cost than direct connected machines. Moreover, when connected to line shaft they are run by the main engine which as a rule is more efficient than a small engine direct connected.

Where there is sufficient room between pulley centers, a belt is a satisfactory medium for power transmission, and one that is largely used.

It is important that there be liberal distance between centers, especially in the case of alternators or motors belted to a medium or slow speed engine, because, owing to the high speed of rotation of the electric machines, there

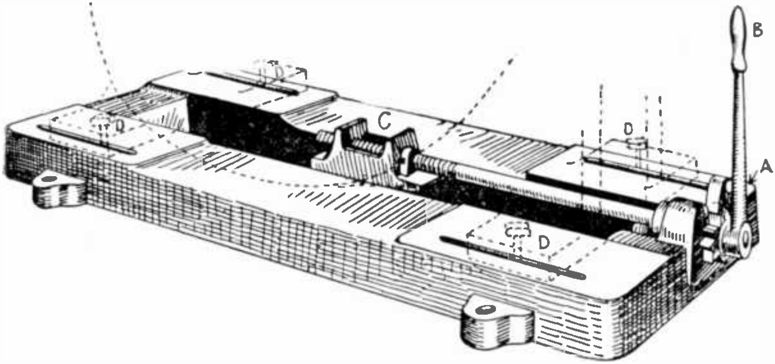


FIG. 2,161.—Sub-base and ratchet device for moving alternator to tighten belt. A ratchet A, operated by lever B, works the block C, by screw connection, causing it to move the block. The latter, engaging with the frame, causes it to move, thus providing adjustment for belt. After tightening belt, the bolts D, which pass through the slots in the sub-base, are tightened, thus securing the machine firmly in position.

is considerable difference in their pulley diameters and the drive pulley diameter; hence, if they were close together, the arc of contact of the belt with the smaller pulley would be appreciably reduced, thus diminishing the tractive power of the belt.

Ques. What provision should be made in the design of an alternator to adapt it to belt drive?

Ans. Provision should be made for tightening the belt.

Ques. How is this done?

Ans. Sometimes by an idler pulley, but usually by mounting the machine on a sub-base provided with slide rails, as in

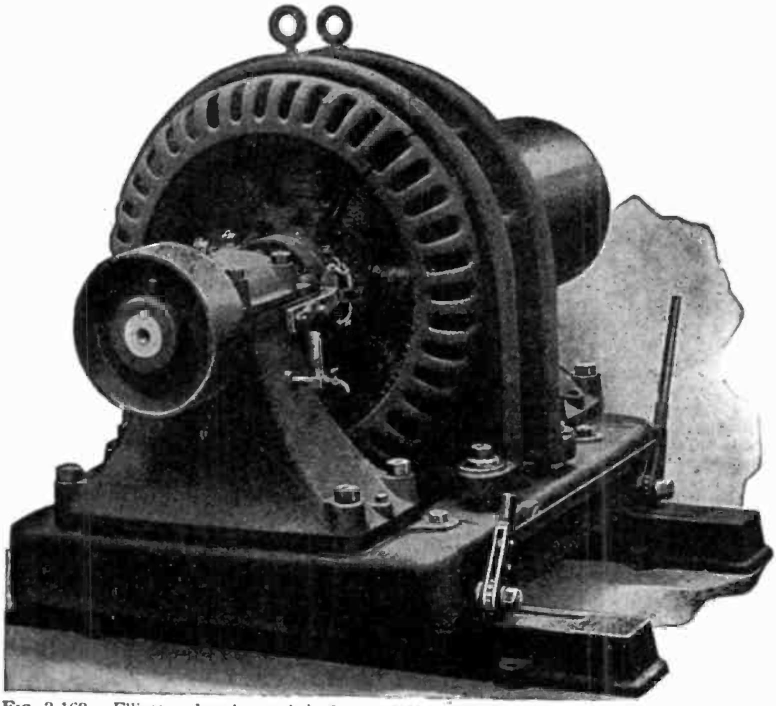


FIG. 2,162.—Elliott pedestal type belted alternator. Belted alternators have their armatures mounted on a substantial cast iron base provided with slide rails and a ratchet shifting device for tightening the belt. The revolving field is carried on a heavy forged steel shaft having journals of large diameter running in self-oiling and self-aligning bearings lined with babbitt. The bearing pedestals are separate from the base and are firmly bolted and doweled thereto. A suitable main driving pulley and an exciter driving pulley are always included unless otherwise specified. Coupled type alternators for direct connection to water wheels or gas engines are built the same as belted alternators, except that the slide rails and belt tightening device are omitted and the pulley is replaced by a flange coupling.

fig. 2,161, the belt being tightened by use of a ratchet screw which moves the machine along the base.

Ques. Give a rule for obtaining the proper size of belt to deliver a given horse power.

Ans. *A single belt traveling at a speed of one thousand feet per minute will transmit one horse power; a double belt will transmit twice that amount.*

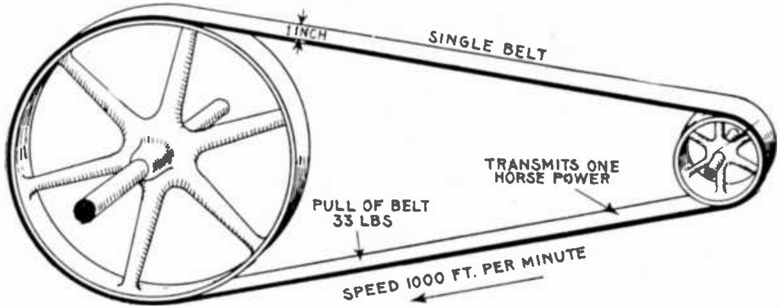


FIG. 2,163.—Diagram illustrating rule for horse power transmitted by belts. *A single belt traveling at a speed of 1,000 feet per minute will transmit one horse power; a double belt will transmit twice that amount*, assuming that the thickness of a double belt is twice that of a single belt. This is conservative practice, and a belt so proportioned will do the work in practically all cases. The above rule corresponds to a pull of 33 lbs. per inch of width. Many designers proportion single belts for a pull of 45 lbs. For double belts of average thickness, some writers say that the transmitting efficiency is to that of single belts as 10 is to 7. This should not be applied to the above rule for single belts, as it will give an unnecessarily large belt.

This corresponds to a working strain of 33 lbs. per inch of width for single belt, or 66 lbs. for double belt.

Many writers give as safe practice for single belts in good condition a working tension of 45 lbs. per inch of width.

Ques. What is the best speed for maximum belt economy?

Ans. From 4,000 to 4,500 feet per minute.

Example.—What is the proper size of double belt for an alternator having a 16 inch pulley, and which requires 50 horse power to drive it at 1,000 revolutions per minute full load?

The velocity of the belt is

circumference in feet × revolutions = feet per minute

$$\frac{16}{12}\times 3.1416 \quad \times \quad 1{,}000 \quad = \quad 4{,}188.$$

Horse power transmitted per inch width of double belt at 4,188 feet speed

$$2\times\frac{4{,}188}{1{,}000}=8.38.$$

Width of double belt for 50 horse power

$$50 \div 8.38 = 5.97, \text{ say } 6 \text{ inch.}$$

Ques. What are the advantages of chain drive?

Ans. The space required is much less than with belt drive, as the distance between centers may be reduced to a minimum. It is a positive drive, that is, there can be no slip. Less liability of becoming detached, and, because it is not dependent on frictional contact, the diameters of the sprockets may be much less than pulley diameter for belt drive.

Ques. What are some objections?

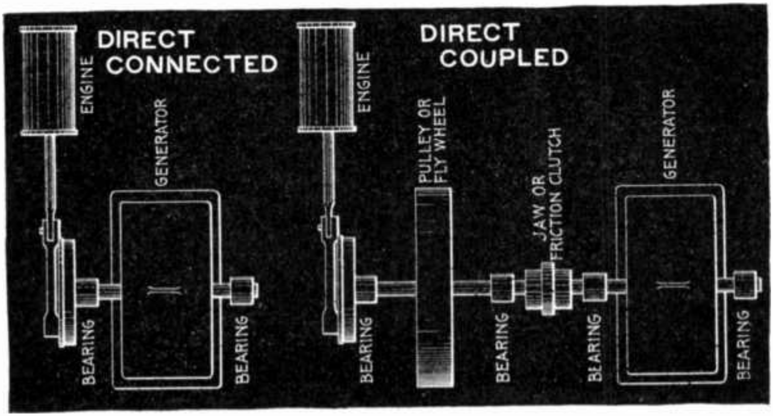
Ans. A lubricant is required for satisfactory operation, which causes more or less dirt to collect on the chain, requiring frequent cleaning; climbing of teeth when links and teeth become worn; noise and friction.

Direct Connected Alternators.—There are a large number of cases where economy of space is of prime importance, and to meet this condition the alternator and engine are direct connected, meaning, that there is no intermediate gearing such as belt, chain, etc., between engine and alternator.

One difficulty encountered in the direct connection of engine and alternator is the fact that the most desirable rotative speed of the engine is less than that of the alternator. Accordingly a compromise is made by raising the engine speed and lowering the alternator speed.

The insistent demand for direct connected units in the small and medium sizes, especially for direct current units, was the chief cause resulting in the rapid and high development of what is known as the "high speed automatic engine."

Increasing the engine speed means that more horse power is developed for any given cylinder dimensions, while reducing the speed of the alternator involves that the machine must be larger for a given output, and



FIGS. 2,164 and 2,165.—Diagram showing the distinction between *direct connected* and *direct coupled* units. In a direct connected unit, fig. 2,164, the engine and alternator are permanently connected on one shaft, there being one bed plate upon which both are mounted. An engine and alternator are said to be direct coupled when each is independent, as in fig. 2,165, being connected solely by a jaw or friction clutch or equivalent at times when it is desired to run the alternator. At other times the alternator may be disconnected and the engine run to supply power for other purposes.

more poles are required to obtain a given frequency, resulting in increased cost.

The compactness of the unit as a whole, simplicity, and general advantages are usually so great as to more than offset any additional cost of the alternator.

Ques. What is the difference between a direct connected and a direct coupled unit?

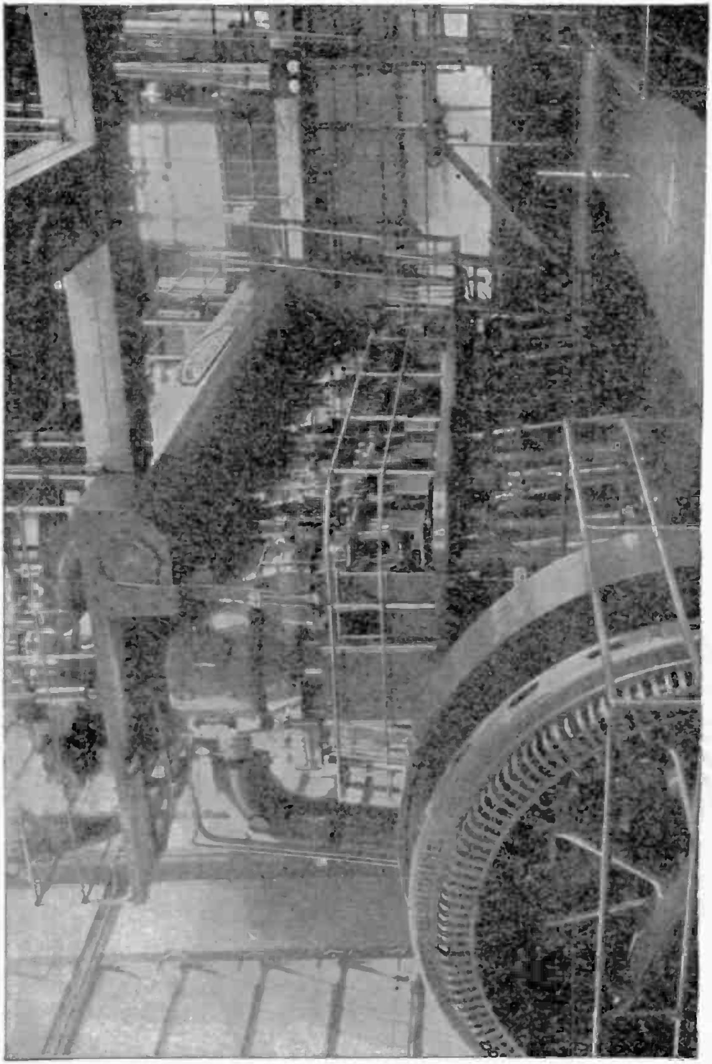
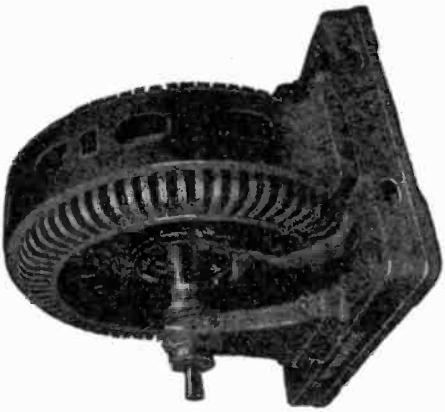


FIG. 2,166.—Westinghouse 1,600 *kw.* alternator direct connected to 2,250 *h.p.* Nordberg Diesel engine as installed in the Punta Gorda Diesel Electric Station of Florida Power and Light Co.



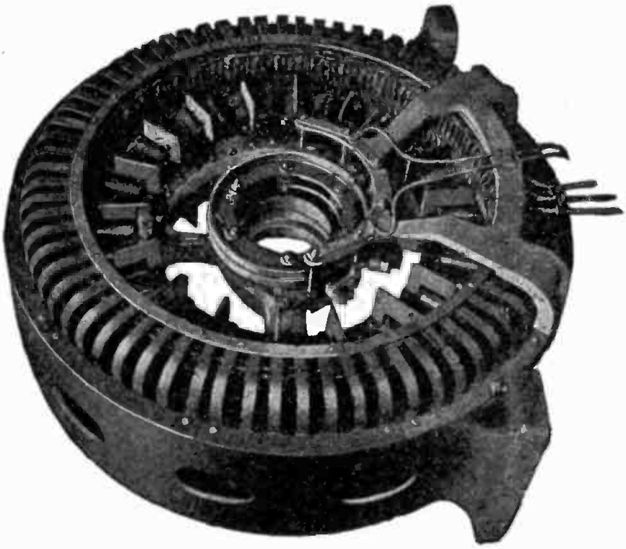


FIG. 2,167.—Westinghouse direct connected engine driven alternator. Capacities 50 to 3,000 *kva*. This type alternator is applicable to all prime movers, being suitable for direct connection to steam, gas or oil engines, or slow speed horizontal water wheels.

FIG. 2,168.—Westinghouse direct coupled alternator for two bearing coupled service.

Ans. A direct connected unit comprises an engine and alternator permanently connected; direct coupling signifies that engine and alternator are each complete in itself, that is, having two bearings, and are connected by some device such as friction clutch, jaw clutch, or shaft coupling. See figs. 2,164 and 2,165.

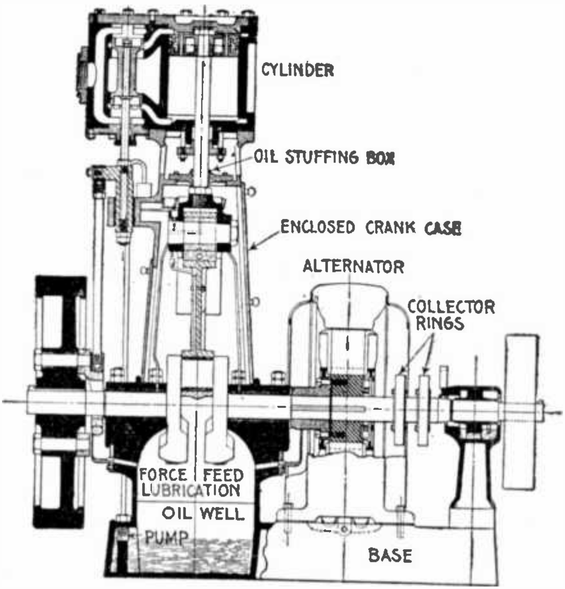


FIG. 2,169.—Endberg direct connected, or "engine type" alternator. In many places direct connected units are used, owing to the great saving in floor space, convenience of operation, and absence of belts.

Revolving Armature Alternators.—This type of alternator is one which has its parts arranged in a manner similar to a dynamo, that is, *the armature is mounted on a shaft so it can revolve while the field magnets are attached to a circular frame and arranged radially around the armature*, as shown in fig. 2,170. It may be single or polyphase, belt driven, or direct connected.

Ques. When is the revolving type of armature used and why?

Ans. It is used on machines of small size because the pressure generated is comparatively low and the current trans-

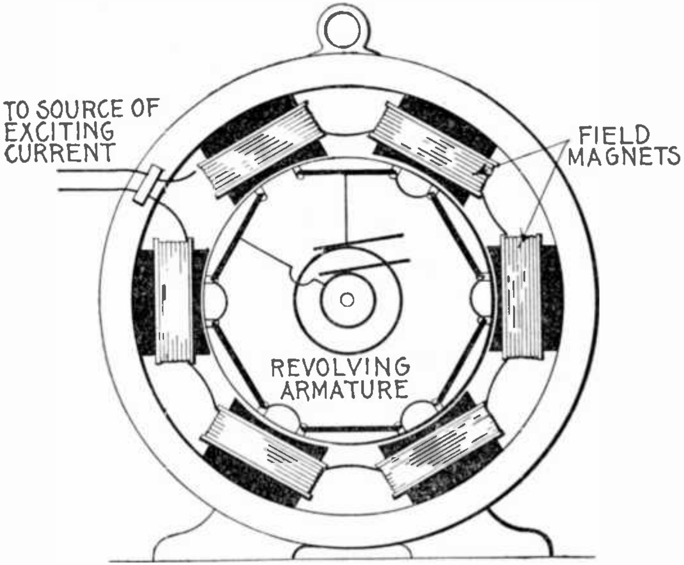


FIG. 2,170.—Revolving armature alternator. Revolving armatures are suitable for machines generating current at comparatively low pressure, as no difficulty is experienced in collecting such current. Revolving armature alternators are also suitable for small power plants, isolated lighting plants, where medium or small size machines are required.

mitted by the brushes small, no difficulty being experienced in collecting such a current.

Ques. Could a dynamo be converted into an alternator?

Ans. Yes.

Ques. How can this be done?

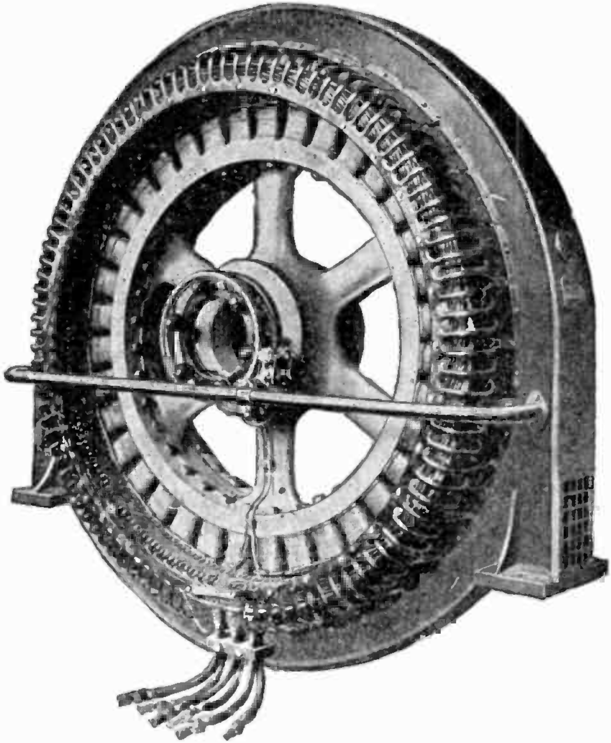


FIG. 2,171.—General Electric 375 *kva*, 200 *r.p.m.* slow speed synchronous alternator for direct connection to steam and internal combustion engines. The armature windings consist of coils formed and wound by machine, and filled with moisture resisting compound. Dummy end shields, punched from sheet steel and formed for rigidity are bolted to the stator frame, affording ample protection to the windings. The bent rail support for the brush mechanism is built in one rigid piece which may be quickly unbolted from the stator frame whenever desired. In the largest frames, a vertical support is added for additional strength. The standard rotor spiders are cast in one piece, and in the smaller sizes are provided with a split hub to facilitate mounting on the shaft without pressing. The pole pieces are made of laminations assembled under pressure and securely bolted to the rim of the spider. The field coils are compactly wound, and insulated from the pole piece and spider. The poles are kept from loosening by lock washers. Any complete pole can easily be removed. An amortisseur winding is provided when machine is to be connected to internal combustion engines. This winding consists of bars inserted in holes in the pole tips and silver soldered to heavy end rings, which are sectionalized to permit easy removal of any complete pole.

Ans. By placing two collector rings on one end of the armature and connecting these two rings to points in the armature winding 180° apart, as shown in fig. 2,172.

Ques. Would such arrangement as shown in fig. 2,172 make a desirable alternator?

Ans. No.

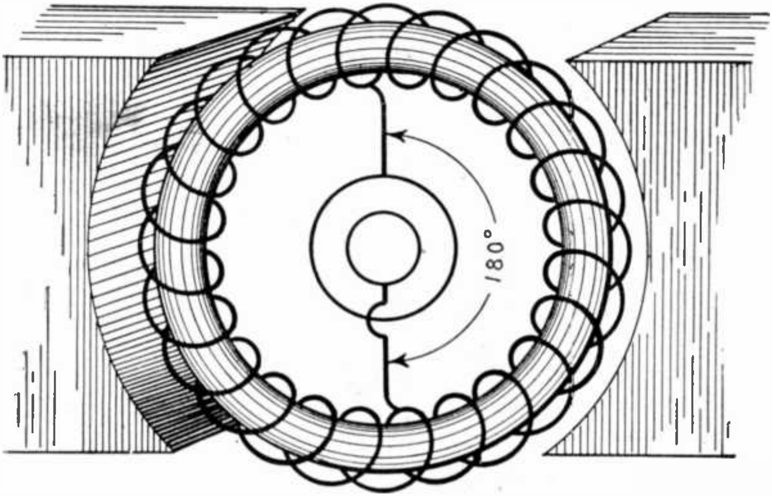


FIG. 2,172.—Ring wound dynamo arranged as alternator by replacing commutator with collector rings connected to the winding at points 180° apart.

Alternating current windings are usually different from those used for direct currents. One distinction is the fact that a simple open coil winding may be, and often is, employed, but the chief difference is the intermittent action of the inductors.

In a direct current Gramme ring winding a certain number of coils are always active, while those in the space between the pole pieces are not generating. In this way a practically steady pressure is produced by a large fraction of the coils.

In the case of an alternator all of the coils are either active or inactive at one time. Hence, the winding need cover only as much of the armature as is covered by the pole pieces.

Revolving Field Alternators.—In generating an electric current by causing an inductor to cut magnetic lines, *it makes no*

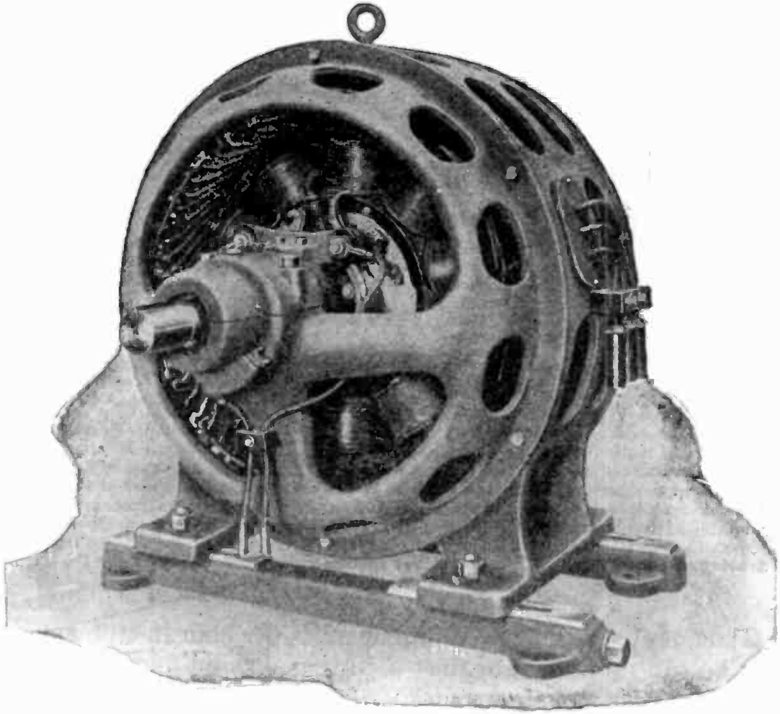


FIG. 2,173.—Allis-Chalmers revolving field self-contained belted type alternator.

difference whether the cutting of the magnetic lines is effected by moving an inductor across a magnetic field or moving the magnetic field across the inductor.

Motion is purely a relative matter, that is, an object is said to move when it changes its position with some other object regarded as stationary; it may be moving with respect to a second object, and at the same time be at rest with respect to a third object.

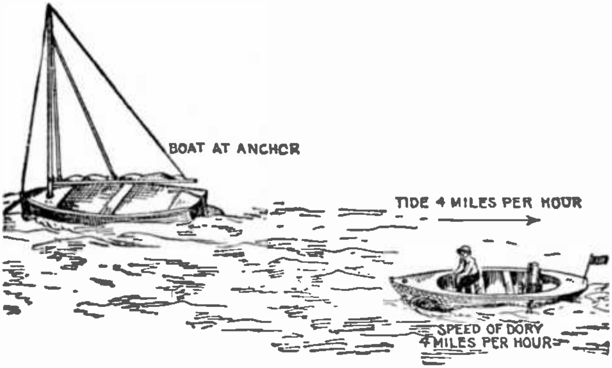


FIG. 2,174.—Marine view, showing that motion is purely a relative matter. In order that there may be motion something must be regarded as being stationary. In the above illustration a cat boat is shown at anchor in a stream which is flowing at a rate of four miles per hour in the direction of the arrow. The small dory running at a speed of four miles per hour against the current is *moving* at that velocity *relative* to the current, yet is at a standstill relative to the cat boat. In this instance both cat boat and dory are moving with respect to the water if the latter be regarded as stationary. Again if the earth be regarded as being stationary, the two boats are at rest and the water is moving relative to the earth.

Thus, a dory has a speed of four miles per hour in still water; if it be run up stream against a current flowing four miles per hour it would move at that speed with respect to the water, yet remain at rest with respect to the earth.

It must be evident then that motion, as stated, being a purely relative matter, ***it makes no difference*** *whether the armature of an alternator move with respect to the field magnets, or the field magnets move with respect to the armature*, so far as inducing an electric current is concerned.

For alternators of medium and large size the armature should be stationary and the field magnets revolve because:

1. By making the armature stationary, superior insulation

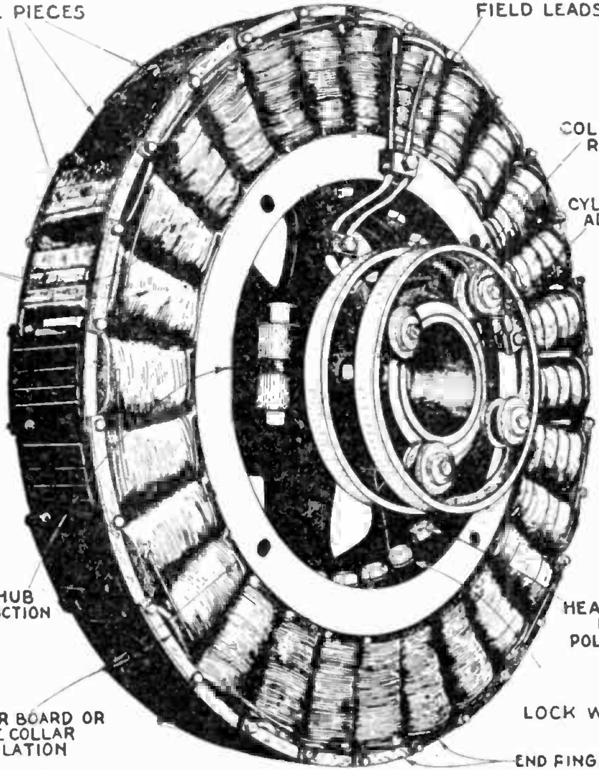


FIG. 2,175.—Revolving field of General Electric 375 *kva.*, 200 *r.p.m.* slow speed synchronous alternator. The complete machine is shown in fig. 2,171.

methods may be employed, enabling the generation of current at very much higher voltage than in the revolving armature type.

2. The difficulty of taking current at very high pressure from collector rings is avoided.

The field current only passes through the collector rings. Since the field current is of low voltage and small in comparison with the main current, small brushes are sufficient and sparking troubles are avoided.

3. Only two collector rings are required.

4. The armature terminals being stationary, may be enclosed permanently so that no one can come in contact with them.

Ques. What names are usually applied to the armature and field magnets with respect to which moves?

Ans. The "stator" and the "rotor."

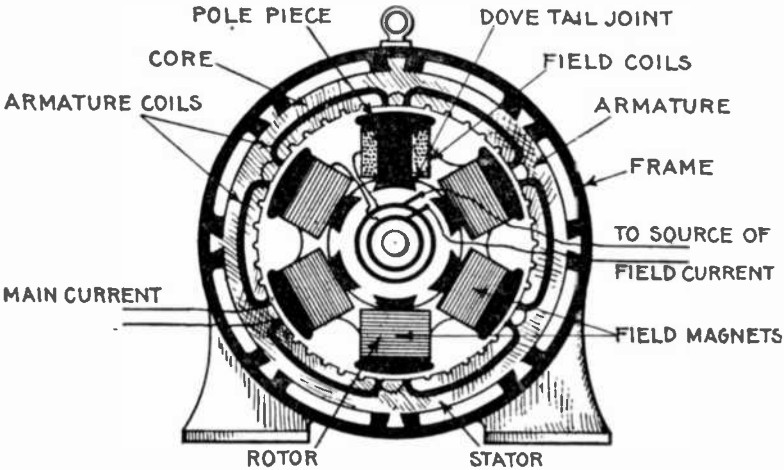


FIG. 2,176.—Diagram showing essential parts of a revolving field alternator and method of joining the parts in assembling.

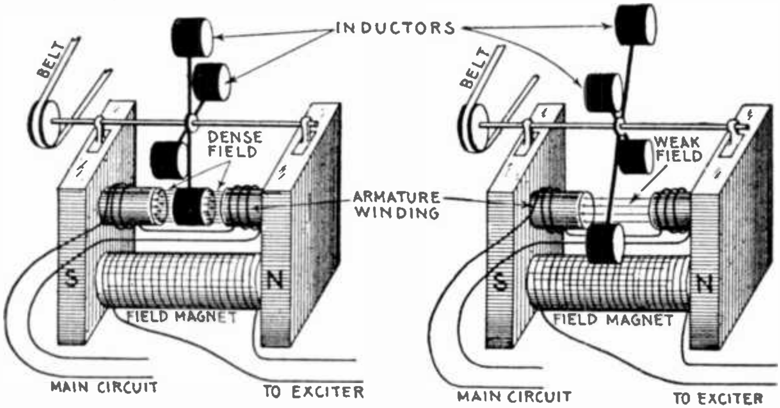
The terms armature and field magnets are to be preferred to such expressions. An armature is an armature, no matter whether it move or be fixed, and the same applies to the field magnets. There is no good reason to apply other terms which do not define the parts.

Ques. Describe the construction of a revolving field alternator.

Ans. The construction of such alternators is indicated in the diagram, fig. 2,176.

Attached to the shaft is a field core, which carries the latter, consisting of field coils fitted on pole pieces which are dovetailed to the field core. The armature is built into the frame and surrounds the magnets as shown. The field current, which is transmitted to the magnets by slip rings and brushes consists of direct current of comparatively low pressure, obtained from some external source.

Inductor Alternators.—In this class of alternator *both armature and field magnets are stationary, a current being induced*

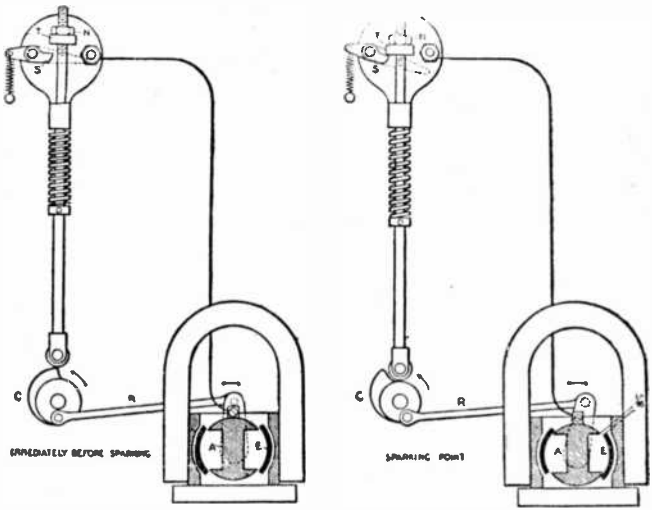


FIGS. 2,177 and 2,178.—Elementary inductor alternator; diagram showing principle of operation. ***It consists of*** a field magnet, at the polar extremities of which is an armature winding both being stationary as shown. Inductors consisting of iron discs are arranged on a shaft to rotate through the air gap of the magnet poles. Now in the rotation of the inductors, when any one of them passes through the air gap as in fig. 2,177, the reluctance or magnetic resistance of the air gap is greatly reduced, which causes a corresponding increase in the number of magnetic lines passing through the armature winding. Again as an inductor passes out of the air gap as in fig. 2,178, the number of magnetic lines is greatly reduced; that is, when an inductor is in the air gap, the magnetic field is dense, and when no inductor is in the gap, the field is weak; a variable flux is thus made to pass through the armature winding, inducing current therein. The essential feature of the inductor alternator is that iron only is revolving, and as the design is usually homopolar, the magnetic flux in its field coils is not alternating, but undulating in character. Thus, with a given maximum flux through each polar mass, the total number of armature turns required to produce a given voltage is just twice that which is required in an alternator having an alternating instead of an undulating flux through its field windings. The above and the one shown in figs. 2,179 and 2,180 are examples of real inductor alternators, other types are simply so called inductor alternators, the distinction being that, as above, the *inductor* constitutes no part of the field magnet.

in the armature winding by the action of a so called inductor in moving through the magnetic field so as to periodically vary its intensity.

Ques. What influence have the inductors on the field flux?

Ans. They cause it to undulate; that is, the flux rises to a maximum and falls to a minimum value, but does not reverse.



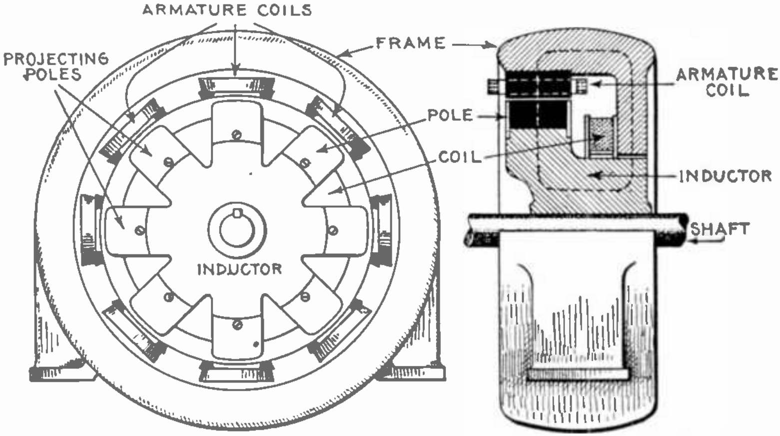
FIGS. 2,179 and 2,180.—A low tension ignition system with an inductor magneto of the oscillating type. The inductor B, is rotated to and fro by means of a link R, one end of which is attached to the inductor crank, and the other to the igniter cam C. Two views are shown: immediately before and after sparking. S, is the grounded electrode of the igniter; T, an adjustable hammer which is secured in position by a lock nut N.

Ques. How does this affect the design of the machine as compared with other types of alternator?

Ans. With a given maximum magnetic flux through each polar mass, the total number of armature turns necessary to produce a given pressure is twice that which is required in an alternator having an alternating flux through its armature windings.

Ques. Is the disadvantage due to the necessity of doubling the number of armature turns compensated in any way?

Ans. Yes, the magnetic flux is not reversed or entirely changed in each cycle through the whole mass of iron in the



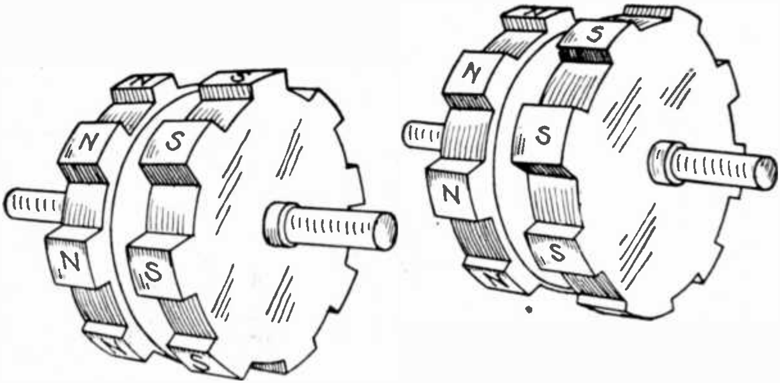
FIGS. 2,181 and 2,182.—One form of inductor alternator. As shown, the frame carries the stationary armature, which is of the slotted type. Inside of the armature is the revolving inductor, provided with the projections built up of wrought iron or steel laminations. The circular exciting coil is also stationary and encircles the inductor, thus setting up a magnetic flux around the path indicated by the dotted line, fig. 2,182. The projecting poles are all, therefore, of the same polarity, and as they revolve, the magnetic flux sweeps over the coils. Although this arrangement does away with collector rings, the machines are not so easily constructed as other types, especially in the large sizes. The magnetizing coil becomes large and difficult to support in place, and would be hard to repair in case of breakdown. Inductor alternators have become practically obsolete, except in special cases, as inductor magnetos used for ignition and other purposes requiring a very small size machine. The reasons for the type being displaced by other forms of alternator are chiefly because only half as great a pressure is obtained by a flux of given amount, as would be obtained in the ordinary type of machine. It is also more expensive to build two armatures, to give the same power, than to build one armature. This type has still other grave defects, among which may be mentioned enormous magnetic leakage, heavy eddy current losses, inferior heat emissivity, and bad regulation.

armature, the abrupt changes being largely confined to the projections on the armature surface between the coils.

Ques. What benefit results from this peculiarity?

Ans. It enables the use of a very high magnetic flux density in the armature without excessive core loss, and also the use of a large flux without an excessive increase in the amount of magnetic iron.

The use of a large flux permits a reduction in the number of armature



FIGS. 2,183 and 2,184.—Homopolar and heteropolar "inductors." Homopolar inductors have their N and S poles opposite each other, while in the heteropolar type, they are "staggered" as shown.

turns, thus compensating, more or less, for the disadvantage due to the operation of only one-half of the armature coils at a time.

Classes of Inductor Alternator.—There are two classes into which inductor alternators may be divided, based on the mode of setting of their polar projections:

1. Homopolar machines;
2. Heteropolar machines.

Homopolar Inductor Alternators.—In this type the positive polar projections of the inductors are set opposite the negative polar projections as shown in fig. 2,183. When the polar projections are set in this manner, the armature coils must be "staggered" or set displaced along the circumference with respect to one another at a distance equal to half the distance from the positive poles to the next positive pole.

Heteropolar Inductor Alternators.—Machines of this class are those in which the polar projections are themselves staggered, as shown in fig. 2,184, and therefore, do not require the staggering of the armature coils.

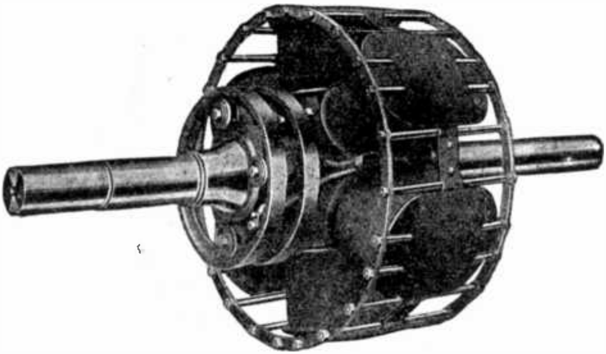


FIG. 2,185.—Revolving field of revolving field alternator equipped with *amortisseur winding*. The object of this winding is to check any tendency toward *hunting* when the alternator is to be run as a synchronous motor, either for rotary condenser or power service. The amortisseur winding consists of heavy copper bars, placed around and through the pole faces and short circuited at the ends by heavy copper rings; it serves as a starting winding to bring the rotor up to speed as an induction motor, and also serves as a damping device to neutralize any tendency toward "hunting" caused by variation in speed of the alternator supplying the current.

In this case, a single armature of double width may be used, and the rotating inductor then acts as a *heteropolar magnet*, or a magnet which presents alternately positive and negative poles to the armature, instead of presenting a series of poles of the same polarity as in the case of a *homopolar magnet*.

Use of Inductor Alternators.—Morday originally designed and introduced inductor alternators in 1866. They are not the prevailing type, as their field of application is comparatively narrow. They have to be very carefully designed with regard to magnetic leakage in order to prevent their being relatively too heavy and costly for their output, and too defective with respect to their pressure regulation, other defects being heavy eddy current losses and inferior heat conductance.

Hunting or Singing in Alternators.—Hunting is a term applied to the state of two parallel connected alternators *running out of step, or not synchronously*, that is, "see-sawing."

When the current wave of an alternator is peaked and two machines

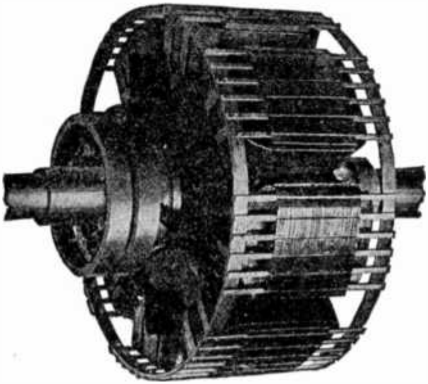


FIG. 2,186.—Revolving field with amortisseur or damper winding of a revolving field 75 *kva.* belted alternator, which prevents hunting and reduces eddy currents in the pole pieces. The copper bars of the amortisseur cage winding are arranged in partially closed slots in the pole pieces.

are operated in parallel it is very difficult to keep them in step, that is, in synchronism. Any difference in the phase relation which is set up by the alternator will cause a local or synchronizing current to flow between the two machines and at times it becomes so great that they must be disconnected.

Alternators which produce a smooth current wave and are maintained at uniform speed by properly designed governors, operate fairly well in parallel, but are not entirely free from hunting, and other means are provided to overcome the difficulty.

When heavy copper flanges, called dampers, are put over the polar projections or copper bars laid in grooves on the pole face and short circuited by connecting rings (called amortisseur winding), the powerful induced currents which are produced when the alternators get out of step tend to quickly re-establish the phase relation.

Two examples of a field provided with amortisseur winding are shown in figs. 2,185 and 2,186.

Monocyclic Alternators.—This type of alternator was designed prior to the introduction of the polyphase systems, to overcome the difficulties encountered in the operation of single phase alternators as motors.

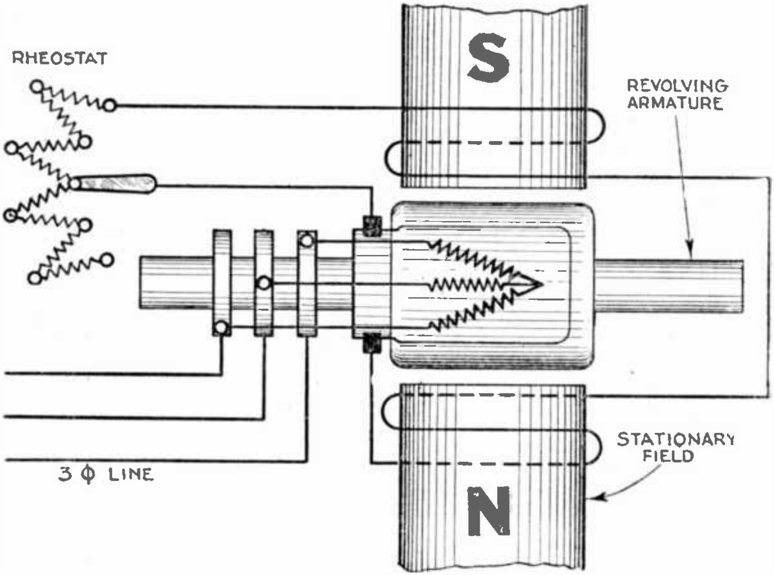
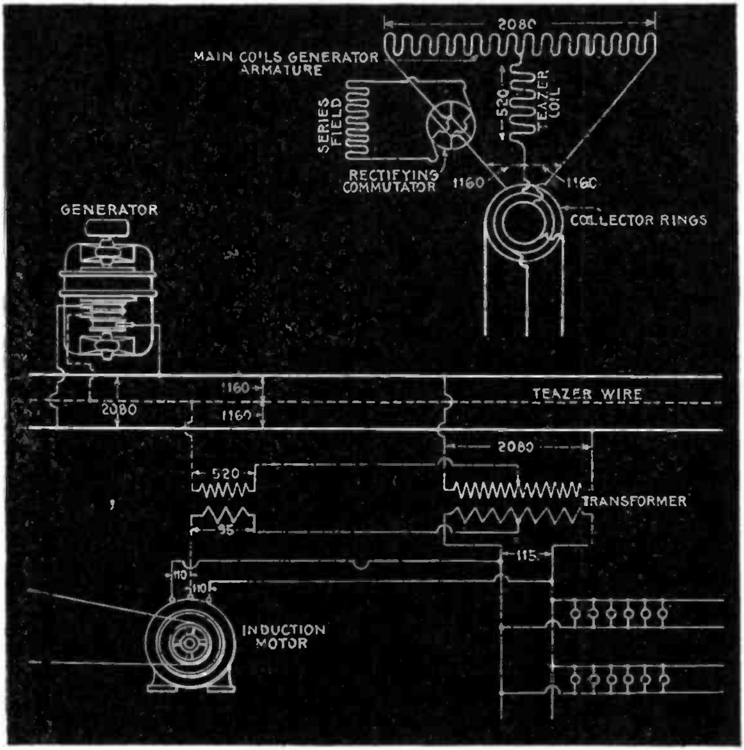


FIG. 2,187.—Connection diagram of General Electric belt driven revolving armature alternator. Illustrations showing construction and general appearance of this machine are shown in the chapter following.

NOTE.—*Amortisseur windings* are often erroneously called "squirrel cage" windings on account of similarity of construction. The latter term should be reserved for its proper significance as being the name of the type of armature winding generally used for induction motors, the name being suggested by the resemblance of the finished armature to the wheel of a squirrel cage. A comparison of figs. 2,186 and 2,632 will show the distinction. In a squirrel cage winding there is a large number of bars uniformly spaced; an amortisseur winding consists of a comparatively small number of bars, usually unevenly spaced; that is, they are divided into groups with considerable space between the groups, as in fig. 2,186, and less pronounced in fig. 2,185. The bars are short circuited by rings the same as in squirrel cage winding.



FIGS. 2,188 and 2,189.—Diagram of monocyclic system, showing monocyclic armature and transformer connections. The monocyclic system is a single phase system primarily intended for the distribution of lights with an incidental load of motors. The lighting load is entirely connected to one single phase circuit, and the motors are started and operated from this circuit with the assistance of the teazer wire. The long coil indicates the main winding of the armature, which is similar in its arrangement and size to the ordinary armature winding of a single phase alternator. The short coil which connects at one end to the middle point of the coil above mentioned, and at the other to a third collector ring is called the "teazer" coil. Its use is to generate a pressure in quadrature with that of the main coil. This pressure is combined with the main pressure of the alternator by transformers, so as to give suitable phase relations for operating induction motors. In the diagram the voltage has been assumed to be 2,080 volts, and the voltages marked to correspond with the generated pressure. The coils of the alternator armature are connected, as shown, to two main leads and to a teazer wire. Between each end of the main coil and the end of the teazer coils, a resultant pressure is generated. These resultants are about 12 per cent. larger than half the main pressure. They also have a phase difference.

A single phase alternator will not start from rest as does a motor, but must first be started and brought up to proper speed before being connected with single phase mains. This condition constituted a difficulty in all cases where the alternator had to be stopped and started at comparatively frequent intervals.

The monocyclic alternator is *a single phase machine provided with an additional coil, called a* ***teazer coil****, wound in two phase*

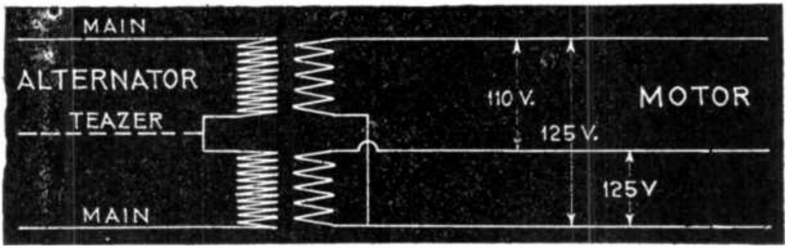


FIG. 2,190.—Monocyclic system diagram showing transformer connections.

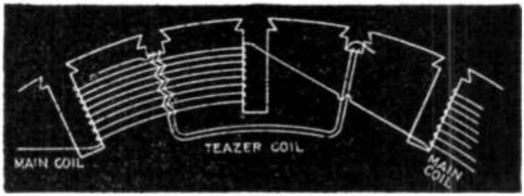


FIG. 2,191.—Diagram showing section of monocyclic alternator armature illustrating the armature winding. The main coils are wound on every other tooth, and the teazer coils are placed in quadrature with them, as shown.

relationship with, and connected to the center of the main single phase coil.

It is provided with three collector rings; two for the single phase coil, and one for the free end of the *teazer coil.*

By this arrangement ordinary single phase incandescent lighting can be accomplished by means of a single pair of wires taken from the single phase coil.

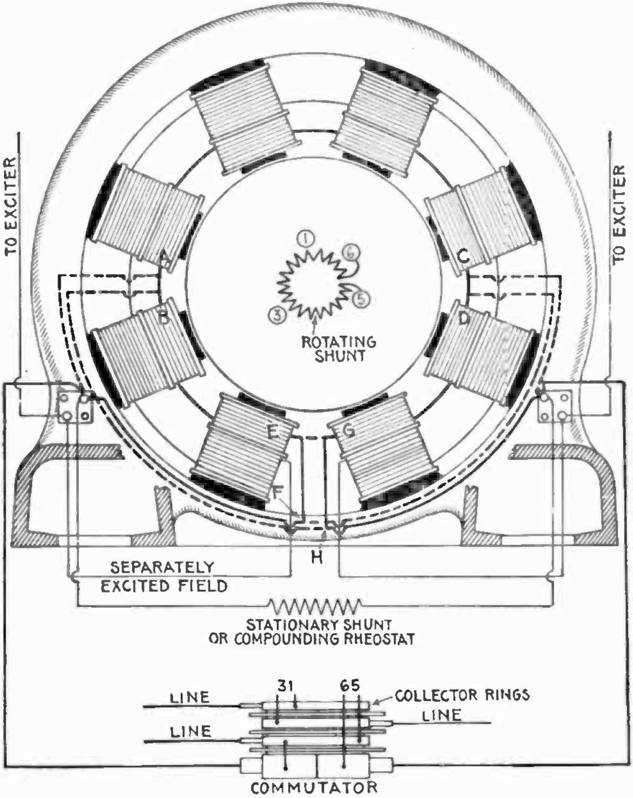


FIG. 2,192.—Diagram showing connections of General Electric monocyclic alternator. For 2,300 volt machine, connect as shown by solid lines. For 1,150 volt machine, omit connections A to B, C to D, E to F, and G to H, and connect as shown by dotted lines. The armature of a standard monocyclic alternator rotates in a counter clockwise direction facing the commutator. When the alternator is loaded, the voltage between the teazer coil and the two terminals of the main coil may be different; therefore, it is necessary to have the commutator connected in corresponding ends of the main coil. If the machine has not been arranged for clockwise rotation, the following change in the connections on the commutator-collector must be made if the machine is to be run in parallel with another. Fig. 2,193 shows the connections of monocyclic alternators. In fig. 2,192, the studs on the commutator-collector marked 1 and 6 are the terminals of the main coil. These should be reversed. The numbers are stamped on the ends of the stud and may be seen with the assistance of a mirror. By referring to this diagram it is a simple matter to trace out the connections with a magneto, after the armature leads are disconnected and the brushes raised.

Where three phase motors have to be operated, however, a third wire, called the *power wire*, which is usually smaller than the main single phase wires is carried to the point at which the motor is located, and by the use of two suitably connected transformers three phase currents are obtained from the combined single phase and power wires for operating the motors.

Figs. 2,188 and 2,189 show the connections of the monocyclic system and it is only necessary to carry the teaser wire into buildings where motors are to be used.

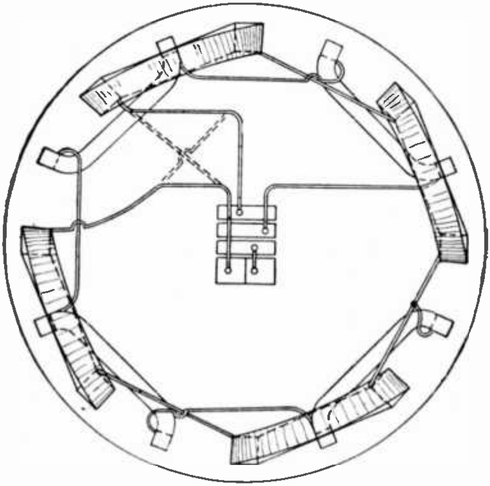


FIG. 2,193.—Diagram showing connections of General Electric monocyclic alternator. The solid lines show standard connections for counter-clockwise rotation; the broken lines show connection changed for clockwise rotation.

Armature Reaction.—Every conductor carrying a current creates a magnetic field around itself, whether it be embedded in iron or lie in air. Armature inductors, therefore, *create magnetic fluxes around themselves, and these fluxes will, in part, interfere with the main flux from the poles of the field magnet.*

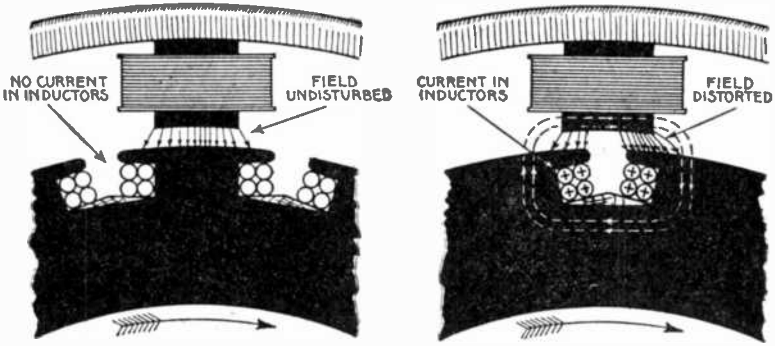
The effect of these fluxes is:

1. To distort the field, or
2. To weaken the field.

These disturbing fluxes form, in part, stray fluxes linked around the armature inductors tending to choke the armature current.

Ques. Explain how the field becomes distorted by armature reaction.

Ans. Considering a slotted armature and analyzing the electrical conditions as the inductors move past a pole piece



Figs. 2,194 and 2,195.—Section of armature and field showing *distorting effect* of armature reaction on the field. When a coil is opposite a pole as in fig. 2,194, no current is flowing (assuming no self-induction) and the field is undisturbed, but, as the inductors pass under a pole face as in fig. 2,195, current is induced in them, and lines of force are set up as indicated by the dotted lines. This distorts the main field so that the lines of force are crowded toward the forward part of the pole face as shown.

it will be observed: 1, when the coil is in the position shown in fig. 2,194, the current will be zero, assuming no armature self-induction, consequently for this position the armature coil has no disturbing effect upon the field set up by the field magnet; 2, when the inductors have moved under the pole face, as in fig. 2,195, currents will be induced in them, and they will tend to set up a magnetic field as indicated by the dotted lines, and in direction, by the arrow heads. The effect of this field will be to distort the main field, strengthening one side of the pole and weakening the other side.

Ques. Explain how the field becomes weakened by armature reaction.

Ans. In all armatures there is more or less inductance which causes the current to lag behind the pressure a corresponding amount. Accordingly, the current does not stop flow-

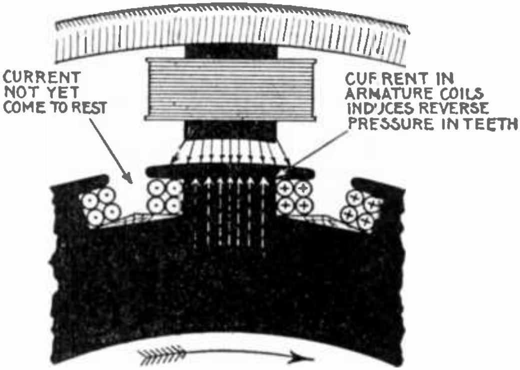


FIG. 2,196.—Section of armature and field showing *weakening effect* of armature reaction in the field. Self induction being present (as it almost always is), the current lags more or less behind the pressure, so that when the coil is in the position of zero induction, as shown, the current has not yet come to rest. Accordingly, lines of force (indicated by the dotted lines) are set up by the current flowing through the coils which are in opposition to the field, thus weakening the latter. The dots and crosses in inductor sections, have their usual significance in defining the direction of current, representing respectively the heads and tails of arrows.

ing at the same instant that the pressure becomes zero, therefore, when the coil is in the position of zero pressure, as in fig. 2,196, the current is still flowing and sets up a magnetic field which opposes the main field as indicated by the dotted arrows, thus weakening the main field.

Ques. In what kind of armature is this effect especially pronounced?

Ans. In slotted armatures provided with coils of a large number of turns.

Ques. What would be the effect if the current lead the pressure?

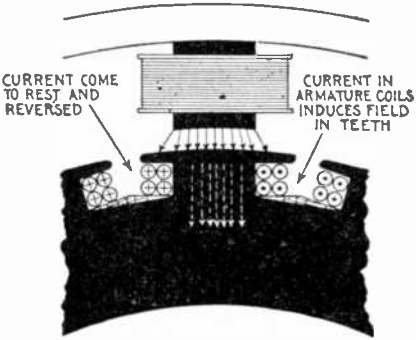


FIG. 2,197.—Section of armature and field showing ***strengthening effect*** of armature reaction when the current leads the pressure. If the circuit contain an excess of capacity the current will lead the pressure, so that when the coil is in the position of zero induction, as shown, the current will have come to rest and reversed. Accordingly, lines of force (indicated by the dotted lines) are set up by the current flowing through the coil and which are in the same direction as the lines of force of the field, thus strengthening the latter.

Ans. It would tend to strengthen the field as shown in fig. 2,197.

The value of the armature ampere turns which tend to distort and to diminish or augment the effect of the ampere turns on the field magnet is sometimes calculated as follows:

$$A = \frac{.707 \times I \times T \times P}{s}$$

in which

A = armature ampere turns;
I = current per phase;
T = turns per pole per phase;

P = number of phases;
s = product of the distribution and pitch factors of the winding.

This value of ampere turns, combined at the proper phase angle with the field ampere turns gives the value of the ampere turns available for producing useful flux.

Single Phase Reactions.—Unlike three phase currents, a single phase current in an alternator armature produces a periodic disturbance of the flux through the machine. In the magnet system this disturbance

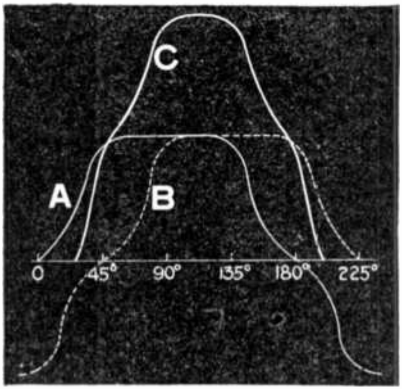
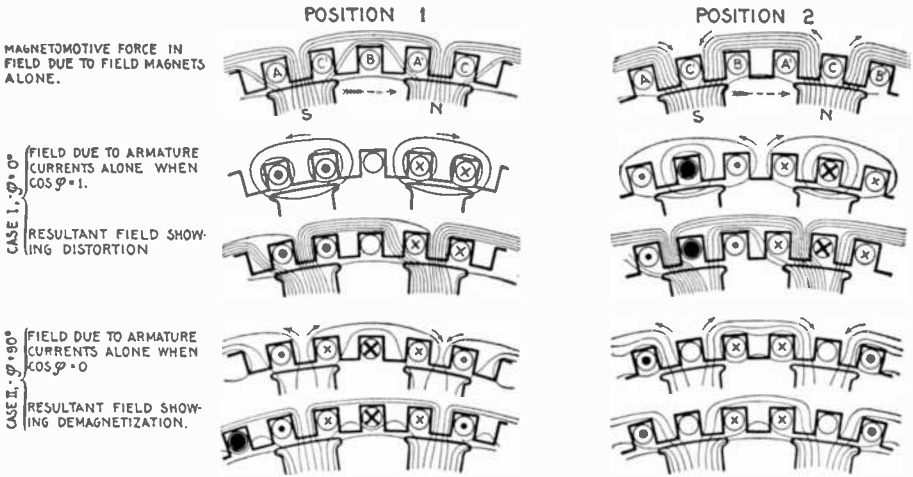


FIG. 2,198.—Alternator wave shape. The sine curve is the desirable shape. A non-sinusoidal form can be resolved into a fundamental and several harmonics of definite amplitudes, all of which are of sine wave shape. The presence of such harmonics of various frequencies in a machine supplying a system with complex connections is apt to result in a resonant response of some part of the circuit. Localized excessive pressures or currents are then likely to develop and cause damage. Since waves can be approximated by carefully shaping the pole pieces, but manufacturers seldom resort to this method. Most alternators have a flux distribution somewhat like that represented by curve A. This curve would also be the pressure wave shape produced by such a flux distribution in a concentrated full pitch winding. If, however, the winding be distributed or be formed of short pitch coils, the resultant wave would be more nearly sinusoidal. For a 135° pitch concentrated winding, or a full pitch winding distributed in two slots per phase per pole with an angular slot separation of 45 electrical degrees, the resultant wave would have the shape of curve C, which is obtained by adding the ordinates of two similar curves A and B displaced 45 degrees from each other. It will be observed that curve C, approximates much nearer to a sine curve than does either of its components. By proper distribution of phase belts and selection of coil pitch a practically sine wave shape may be attained.

is of twice the normal frequency, while in the armature core it is the same as the normal frequency. In both cases the eddy currents which are set up, produce a marked increase in the load losses, and thus tend to give the machine a higher temperature rise on single phase loading.



FIGS. 2,199 to 2,208.—Diagrams illustrating superposition of fields. In the figures magnetic curves representing the effect of the armature currents in several different cases are superposed upon the magnetic curves assumed to be due to the field magnet. The uppermost line shows the primary field due to the exciting coils on the magnet poles. They are shown passing into the armature teeth in two principal positions, where the middle of a pole is: 1, opposite a tooth, and 2, opposite a slot. In the second line is shown the field due to the armature currents assuming no lag, and that the magnets are not excited. If there be no lag, the places of strongest current will be opposite the poles. As shown in the right hand figure when the current in one phase C, is at its maximum, those in the other phases A and B will be of half strength. In the left hand figure when the current in one phase B, is at its zero value, those in the other phases will be of equal value, or 87 per cent. of the maximum. In the third line is shown the effect of superposing these fields due to the current upon those due to the magnets as depicted in the first line. Inspection of this resultant field shows how the armature current distorts the field without altering the total number of lines per pole. In the fourth and fifth lines are shown the effects of a lagging current. A lag of 90° is assumed; and in that case the maximum current occurs in any inductor one quarter period after the pole has passed, or at a distance of half a pole pitch behind the middle point of the pole, as in the fourth line. When these armature fields are superposed on those of the magnets in the first line the resultant fields are those depicted in the fifth line. On inspection it will be seen that in this case there is no distortion, but a diminution of the flux from each pole, as the lines due to the armature currents, tending to

Designers continue to be singularly heedless of these single phase reactions, resulting in many cases of unsatisfactory single phase alternators. Single phase reactions distort the wave form of the machine.

Three Phase Reactions.—The action of the three phase currents in an alternator is to produce a resultant field which is practically uniform, and which revolves in synchronism with the field system. The resultant three phase reaction, because of its uniformity, produces no great increase in the load losses of the machine, the small additional losses which are present being due to windings not being placed actually in space at 120°, and to the local leakage in the teeth.

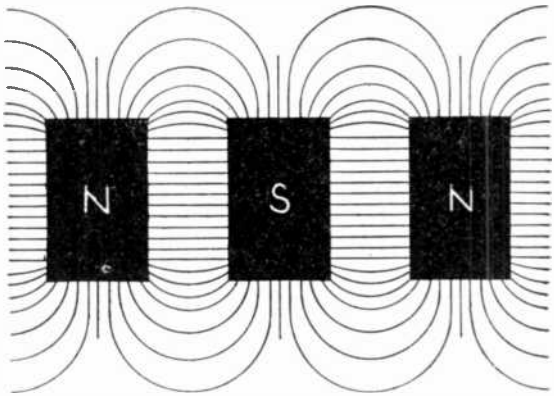


FIG. 2,209.—Diagram showing lateral field between adjacent poles.

Magnetic Leakage.—In the design of alternators *the drop of voltage on an inductive load is mainly dependent upon the magnetic leakages, primary and secondary.*

They increase with the load, and, what is of more importance, they increase with the fall of the power factor of the circuit on which they may be working. This is one reasom why certain types of alternator, though satisfactory on a lighting circuit, have proved themselves unsatisfactory when applied to a load consisting chiefly of motors.

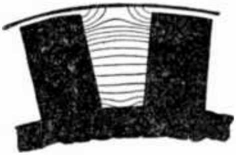
FIGS. 2,199 to 2,208.—*Text continued.*

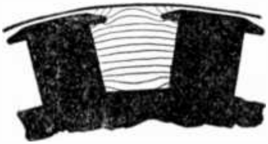
pass through the pole cores in the sense opposite to those of the primary magnetism, must be deducted from the total. The twelve lines per pole are correspondingly reduced to eight; and, of these eight, four go astray constituting a leakage field. This illustrates the effect of a lagging current in demagnetizing the field magnets and in increasing the dispersion.

The designer must know the various causes which contribute to leakage and make proper allowance.

In general, to keep the leakage small, the pole cores should be short, and of minimum surface, the pole shoes should not have too wide a span nor be too thick, nor present needless corners, and the axial length of the pole face and of the armature core should not be too great in proportion to the diameter of the working face.

To keep the increase of leakage between no load and full load from undue magnitude, it is required that armature reactions shall be relatively small, that the peripheral density of the armature current (ampere-conductors per inch) be not too great, and that the pole cores be not too highly saturated when excited for no load.





FIGS. 2,210 and 2,211.—Diagram showing respectively the character of stray field between adjacent straight poles, and between adjacent poles with shoes. Across the slightly V-shaped spaces the stray field passes in lines that, save near the outer part, are nearly straight. Quite straight they would not be, even were the sides parallel, because the difference of magnetic pressure increases from the roots toward the pole ends. At the roots, where the cores are attached to the yoke, the magnetic pressure difference is almost zero. It would be exactly zero if there were not a perceptible reluctance offered by the joints and by the metal of the yoke. The reluctance of the joint causes a few of the lines to take paths through the air by a leakage which adds to the useful flux. At the tops of the core there is a difference of magnetic pressure equal to the sum of the ampere-turns on the two cores, tending to drive magnetic lines across. This difference of magnetic pressure increases regularly all the way up the cores from root to top; hence, the average value may be taken as equal to the ampere turns on one core. The stray field, therefore, will steadily increase in density from the bottom upward. In addition to this stray field between the pole cores there is also a stray field between the projecting tips or edges of the pole shoes, as shown in fig. 2,211. In some machines the dispersion due to the pole shoes is greater than that between the flanks of the cores.

The general character of the stray field between adjacent poles is shown in figs. 2,210 and 2,211 for straight poles and those having shoes.

Field Excitation of Alternators.—The fields of alternators require a separate source of direct current for their excitation, and this current should be preferably automatically controlled.

In the case of alternators that are not self-exciting, the dynamo which generates the field current is called the *exciter*.

The excitation of an alternator at its rated overload and .8 power factor would not, in some cases, if controlled by hand, exceed 125 volts, although, in order to make its armature voltage respond quickly to changes in the load and speed, the excitation of its fields may at times be momen-

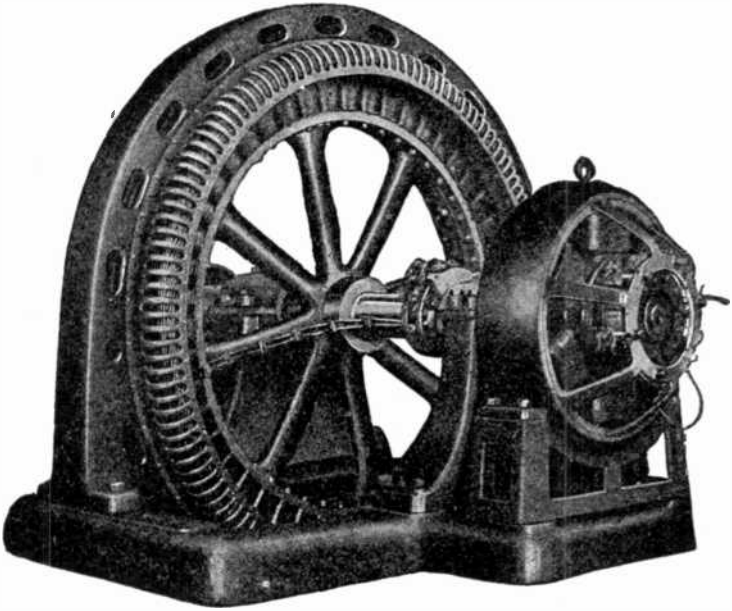


Fig. 2,212.—General Electric alternator with direct connected type M P L exciter mounted on the field shaft at such distance as to permit a pedestal and bearing to be mounted between the exciter and revolving field.

tarily varied by an automatic regulator between the limits of 70 and 140 volts.

The exciter should, in turn, respond at once to this demand upon its armature, and experience has shown that to do this its shunt fields must have sufficient margin at full load to deliver momentarily a range from 25 to 160 volts at its armature terminals.

It is obvious from the above that an exciter suitable for use with an automatic regulator must commutate successfully over a wide range in voltage, and, if properly designed, have liberal margins in its shunt fields and magnetic circuits.

Alternator fields designed for and operated at unity power factor have often proved unsatisfactory when the machines were called upon to deliver their rated *kva*. at .8 power factor or lower. This is due to the increased field current required at the latter condition and results, first, in the overheating of the fields and, second, in the necessity of raising the direct current exciting voltage above 125 volts, which often requires the purchase of new exciters.

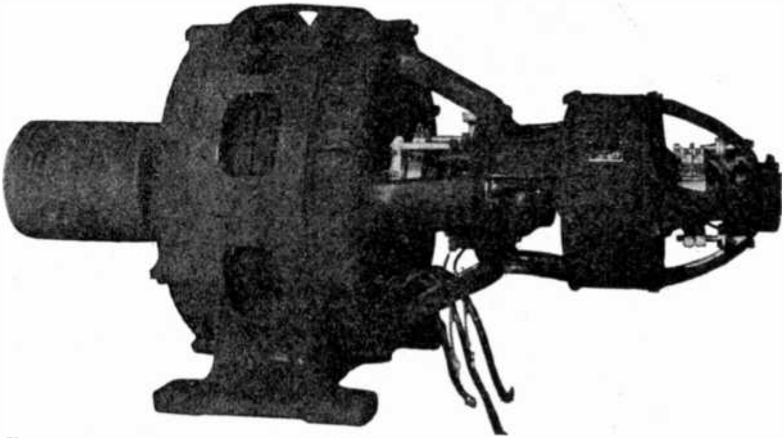


FIG. 2,213.—Westinghouse type SK alternator with revolving armature and direct connected exciter.

Ques. What is a self-excited alternator?

Ans. One whose armature has, in addition to the main winding, another winding connected to a commutator for furnishing direct field exciting current, as shown in fig. 2,257.

Ques. How is a direct connected exciter arranged?

Ans. The exciter armature is mounted on the shaft of the alternator close to the spider hub, or in some cases at a distance sufficient to permit a pedestal and bearing to be mounted between the exciter and hub. In other designs the exciter is placed between the bearing and hub.

The accompanying illustrations are examples of direct connected exciter alternators. In some designs the exciter is placed between the field hub and bearing, and in others, beyond the bearing.

Ques. What is the advantage of a direct connected exciter?

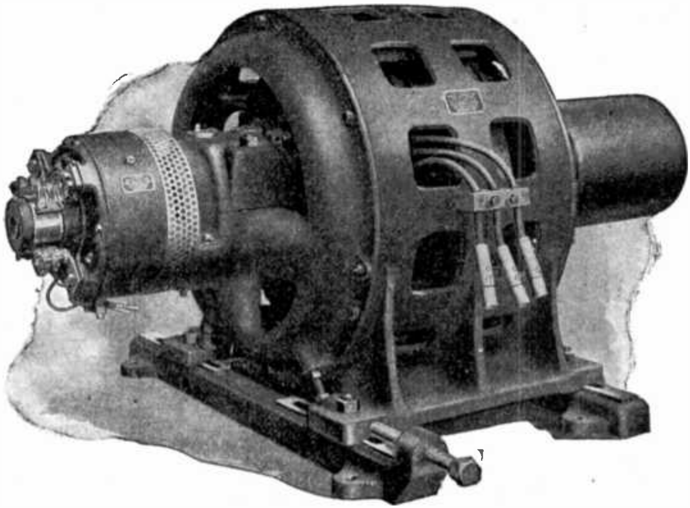
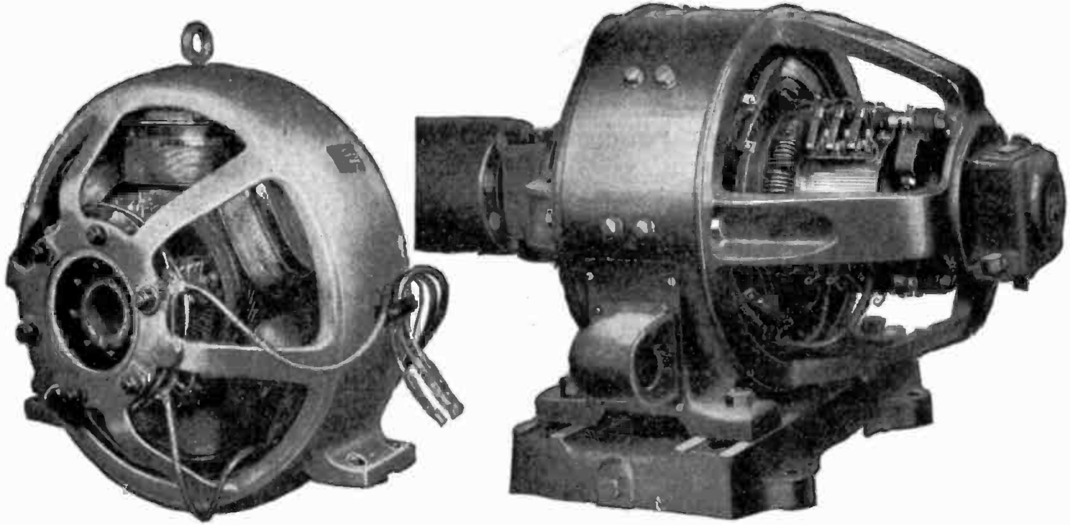


FIG. 2,214.—Allis Chalmers 225 *kva*; 900 *r.p.m.* belted alternator with direct connected exciter.

Ans. Economy of space.

This is apparent by comparing figs. 2,212 and 2,214 with fig. 2,217, which shows a belted exciter.

Ques. What is the disadvantage of a direct connected exciter?



Figs. 2,215 and 2,216.—General Electric exciters. Fig. 2,215, direct connected exciter; fig. 2,216, belted exciter.

Ans. It must run at the same speed as the alternator, which is slower than desirable, hence the exciter must be larger for a given output than the gear driven type, because the latter can be run at high speed and accordingly be made proportionally smaller.

Ques. What form of gear is generally used on gear driven exciters?

Ans. Belt gear.

Ques. What are the advantages of gear driven exciters?

Ans. Being geared to run at high speed, they are smaller and therefore less costly than direct connected exciters. In large plants containing a number of alternators one exciter

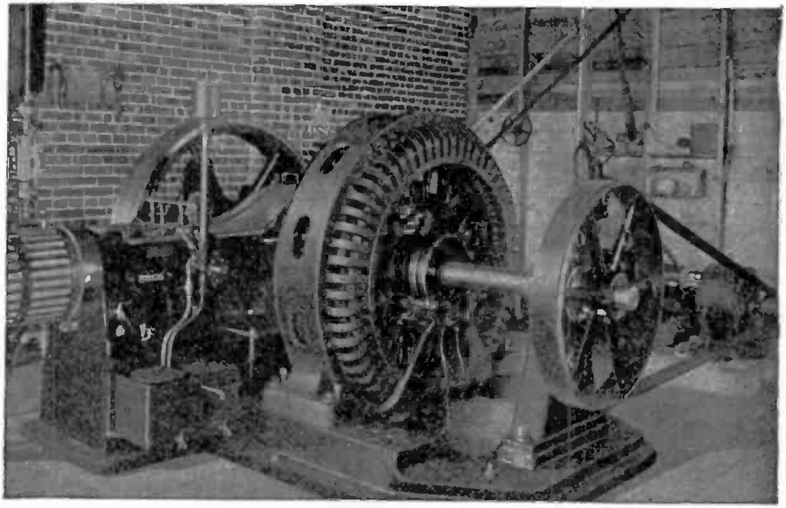


FIG. 2,217.—Diagram showing a Westinghouse 50 *kva.*, 2,400 volt, three phase, 60 cycle revolving field separately excited alternator direct connected to a steam engine. The exciter is belted to the alternator shaft, the driving pulley being located outside the main bearing. The small pulley on the exciter gives an indication of its high speed as compared with that of the alternator.

may be used having sufficient capacity to excite all the alternators, and which can be located at any convenient place.

Ques. What is the disadvantage of gear driven exciters?

Ans. The space occupied by the gear.

In the case of a chain drive very little space is required, but for belts, the drive generally used, there must be considerable distance between centers for satisfactory transmission.

Slow Speed Alternators.—By slow speed is here understood *relatively slow speed, such as the usual speeds of reciprocating engines.*

A slow speed alternator is *one designed to run at a speed slow enough that it may be direct connected to an engine.*

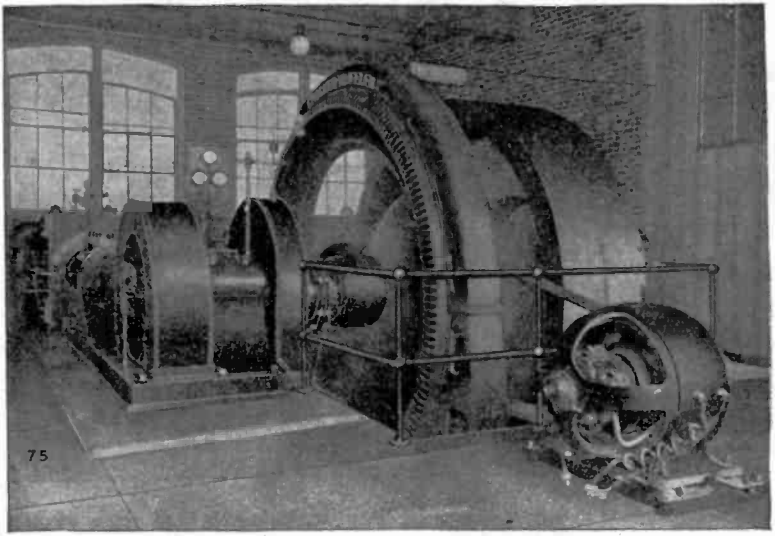


FIG. 2,218.—Crocker-Wheeler 350 *kva.*, slow speed alternator direct connected to a Corliss engine. In front is seen a belted exciter driven from a pulley on the main shaft between the alternator and the large band wheel. The latter serves to give the additional fly wheel effect needed for close speed regulation.

Such alternators are of the revolving field type and a little consideration will show that they must have a multiplicity of field magnets to attain the required frequency.

In order that there be room for the magnets, the machine evidently must be of large size, especially for high frequency.

Example.—How many field magnets are required on a two phase alternator direct connected to an engine running 240 revolutions per minute, for a frequency of 60?

An engine running 240 revolutions *per minute* will turn

$$240 \div 60 = 4 \text{ revolutions } per\ second.$$

A frequency of 60 requires

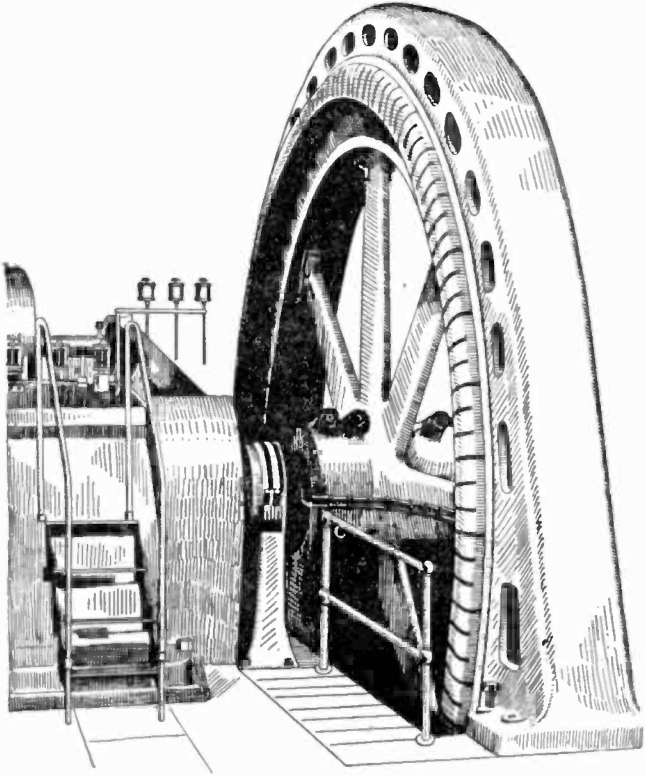


Fig. 2,219.—General Electric 48 pole 750 *kva.*, three phase fly wheel type alternator. It runs at a speed of 150 revolutions per minute, giving a frequency of 60 cycles per second and a full load pressure of 2,300 volts. The slip rings and leads to the field winding are clearly shown in the figure. The field magnets are mounted directly on the rim of the spider, which resembles very closely a fly wheel, and which in fact it is—hence the name "fly wheel alternator."

$$60 \div 4 = 15 \text{ cycles per phase per revolution, or}$$

$$15 \times 2 = 30 \text{ poles per phase.}$$

Hence for a two phase alternator the total number of poles required is

$$30 \times 2 = 60.$$

It is thus seen that a considerable length of spider rim is required to attach the numerous poles, the exact size depending upon their dimensions and clearance.

Fly Wheel Alternators.—The diameter of the revolving fields on direct connected alternators of very large sizes becomes

FIG. 2,220.—Westinghouse rotor for fly wheel type alternator. The revolving field rotor is arranged for direct mounting on the engine shaft. Shaft and bearings are supplied by the maker of the prime mover. The rotor consists of a single steel casting carefully proportioned with reference to cooling strains. To this casting, punched steel laminated poles, securely riveted, are fastened by means of heavy bolts. When the alternators are to be driven by gas or oil engines, cage damper windings are added in order to secure the best parallel operation between units.

so great that considerable fly wheel effect is obtained, although the revolutions be low. By giving liberal thickness to the rim of the spider, the rotor then answers the purpose of a fly wheel, hence no separate fly wheel is required. In fact, the revolving element resembles very closely an ordinary fly wheel with magnets mounted on its rim, as illustrated in fig. 2,219.

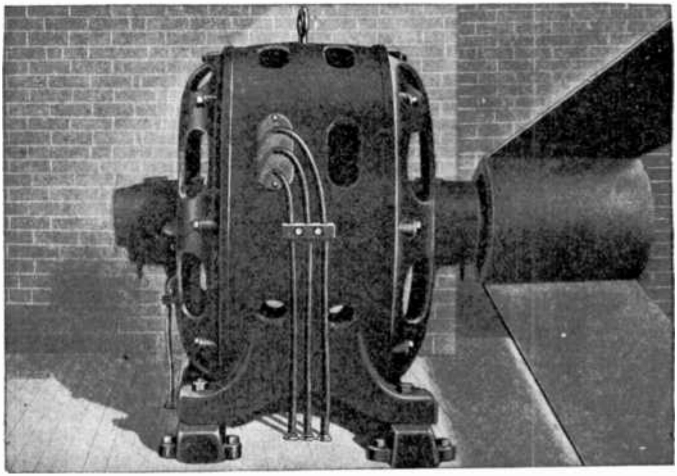


FIG. 2,221.—Allis-Chalmers high speed belted type alternator. The small pulley at the right and the angle of the belt suggest the high speed at which such alternators are run, a 50 *kva*. machine turning 1,200 revolutions per minute.

High Speed Alternators.—Since alternators may be run at speeds far in excess of desirable engine speeds, it must be evident that both size and cost may be reduced by designing them for high speed operation.

Since the desired velocity ratio or multiplication of speed is so easily obtained by belt drive, that form of transmission is generally used for high speed alternators, the chief objection being the space required. Accordingly where economy of space is not of prime importance, a high speed alternator is usually installed, except in the large sizes where the conditions naturally suggest a direct connected unit.

An example of high speed alternator is shown in fig. 2,221. Machines of this class run at speeds of 1,200 to 1,800 or more, according to size.

No one would think of connecting an alternator running at any such speed direct to an engine, the necessary speed reduction proper for engine operation being easily obtained by means of a belt drive.

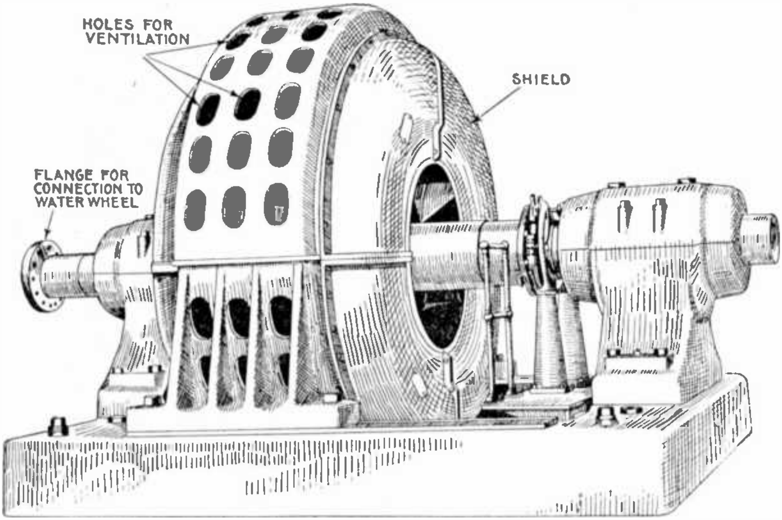
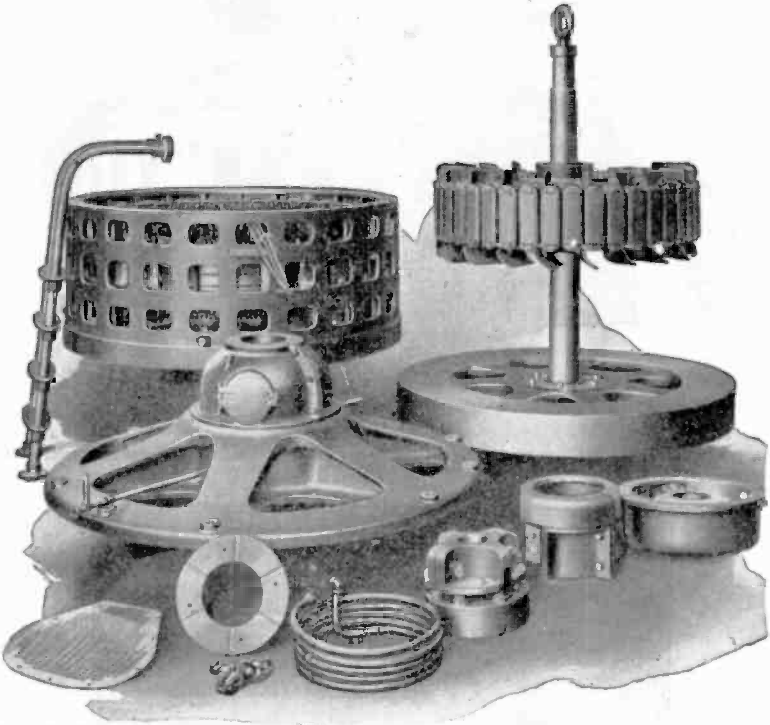


FIG. 2,222.—Allis-Chalmers 5,000 *kva.*, 450 *r. p. m.*, 6,600 volt, 60 cycle, 3 phase, horizontal water wheel alternator. The shaft is extended for the reception of a flange coupling for direct connection to water wheel. Owing to the wide range in output of the generating units and also in the speed at which they must operate to suit varying conditions of head, types of wheels used, and other features pertaining to water power developments, it has been necessary to design a very complete line of machines for this work. The bearings are of the ring oiling type with large oil reservoirs.

Water Wheel Alternators.—In order to meet most successfully the requirements of the modern hydro-electric plant, the alternators must combine those characteristics which result in high electrical efficiency with a mechanical strength of the moving elements which will insure uninterrupted service, and an ample factor of safety when operating at the relatively high speeds often used with this class of machine.



FIGS. 2,223 to 2,233.—Disassembly of Allis Chalmers 200 *kva*; 180 *r.p.m.* vertical water wheel alternator.

When selecting an alternator for water wheel operation a careful analysis of the details of construction should be made in order to determine the relative values which have been assigned by the designers to the properties of the various materials used. Such analysis will permit the selection of a type of machine best adapted to the intended service and which possesses the required characteristics of safety, durability and efficiency.

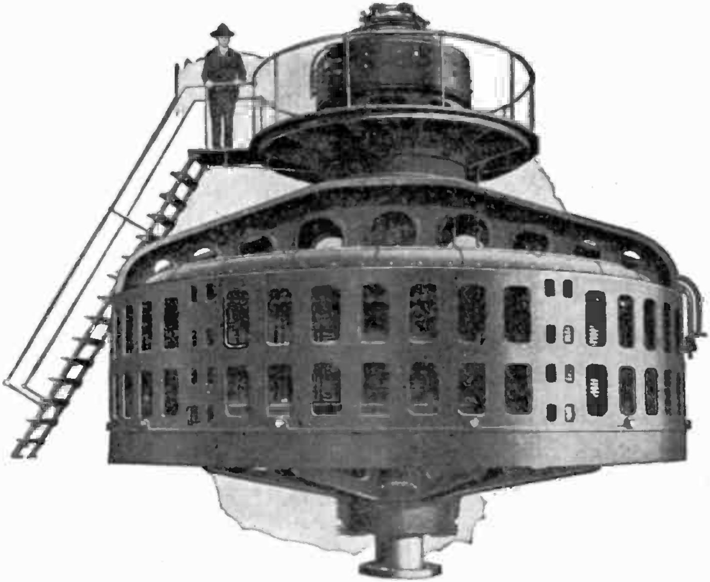


Fig. 2,234.—Allis-Chalmers 18,750 *kva.*, 6,600 volt, 112½ *r.p.m.* vertical water wheel alternator.

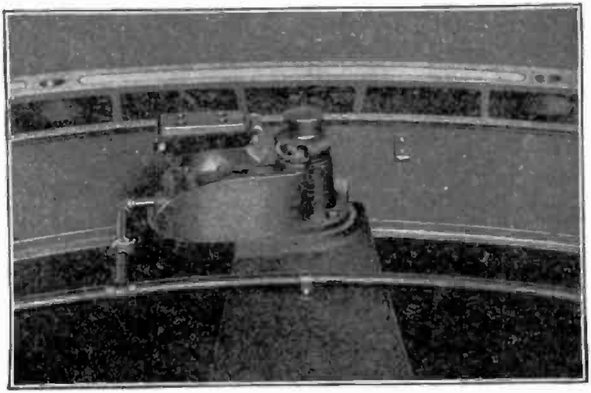
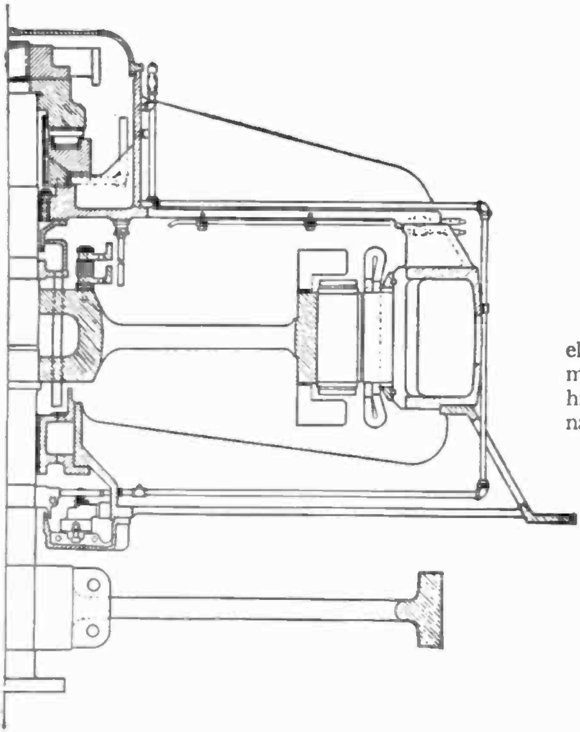


Fig. 2,235.—Allis-Chalmers vertical water wheel alternator brake and lifting jack.



The large use of electric power transmitted by means of high pressure alternating current has

FIG. 2,236.—Westinghouse vertical water wheel alternator; sectional view. *In construction*, the alternator is a self-contained unit, consisting of armature, field, upper guide bearing and bracket, combined lower guide, bearing, bracket and base, thrust bearing, shaft, oiling system and exciter driving pulley.

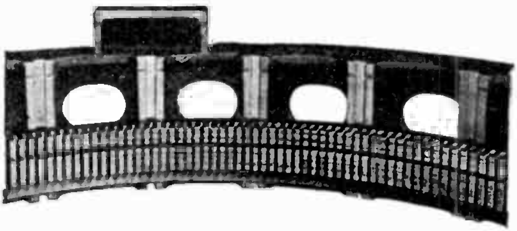
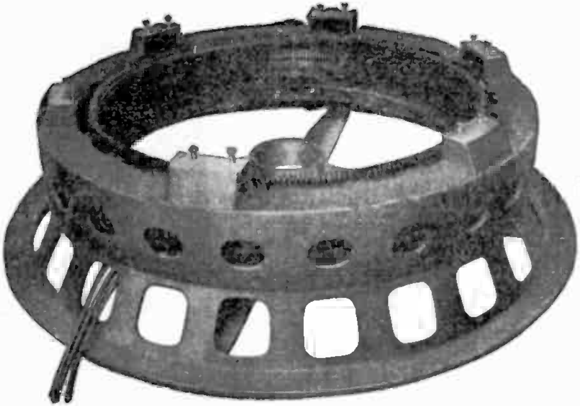


FIG. 2,237.—Westinghouse vertical water wheel alternator armature assembly.



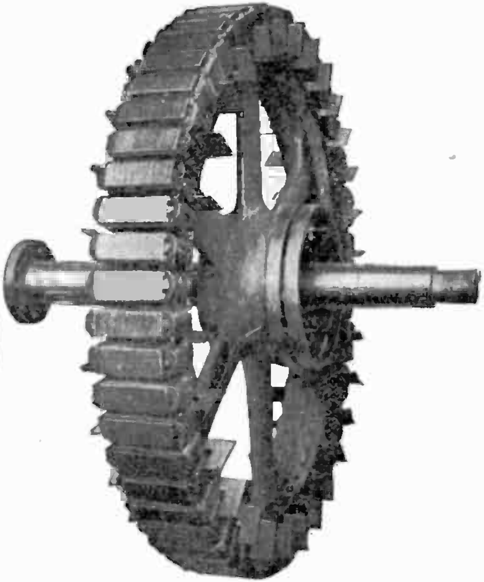


FIG. 2,238.—Westinghouse vertical water wheel alternator armature with armature winding. The frame is of cast iron in which the armature core, built up of annealed and japanned sheet steel punchings, is held by dovetail slots. The open type frame and vent ducts in the armature core assure ample ventilation. The armature winding consists of form wound interchangeable coils, insulated with mica over the imbedded portion and has treated cloth tape on the end turns.

FIG. 2,239.—Westinghouse vertical water wheel alternator complete field with shaft, etc. ***In construction***, a cast steel spider is used, laminated field poles being held to it by at least two bolts per pole. The shaft is of steel with a half flange coupling forged integral with it. The field coils are formed of copper strap on edge, asbestos insulation being used between turns with heavy fibre washers between coil and supporting pole tips and spider respectively. The collector rings, made of cast iron, are supported direct from the spider hub on an insulated brush.

led to the development of a large number of water powers and created a corresponding demand for alternators suitable for direct connection to water wheels.

Ques. Name two forms of water wheel alternator.

Ans. Horizontal and vertical.

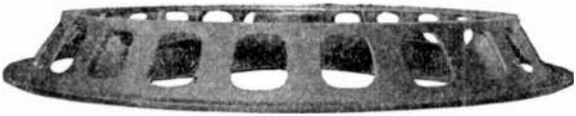


FIG. 2,240.—Westinghouse vertical water wheel alternator base combined with lower guide bearing bracket.

Examples of horizontal and vertical forms of water wheel alternator are shown in the accompanying illustrations.

Ques. How should the rotor be designed?

Ans. It should be of very substantial construction.

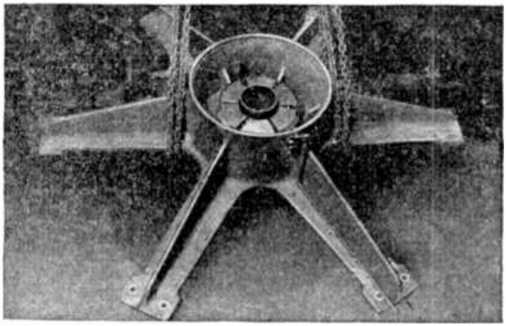


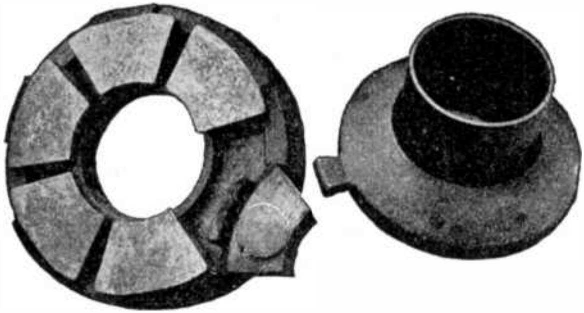
FIG. 2,241.—Westinghouse vertical water wheel alternator upper guide bearing and thrust bearing pot, Kingsbury thrust bearing in place.

Ques. Why?

Ans. Because water wheel alternators are frequently required to operate safely at speeds considerably in excess of normal.

Ques. What special provision is made for cooling the bearings?

Ans. They are in some cases water cooled.



FIGS. 2,242 and 2,243.—Details of Kingsbury thrust bearing for Westinghouse vertical water wheel alternator. The bearing is self-cooled, operating in a bath of oil which is continually circulated by the oiling system.

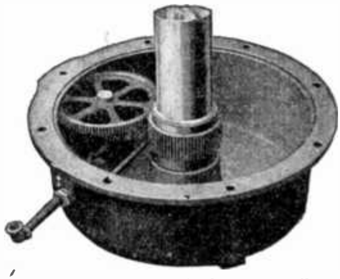


FIG. 2,244.—Westinghouse vertical water wheel alternator oil pan and pump. A positive type of pump geared to the alternator shaft provides continuous lubrication for the two guide bearings and the thrust bearing.

Turbine Driven Alternators.—Although the principle of operation of the steam turbine and that of the reciprocating

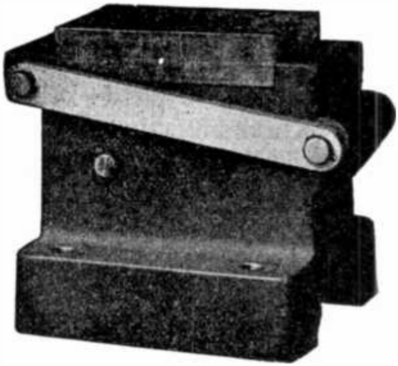


FIG. 2,245.—Westinghouse vertical water wheel alternator brake block.

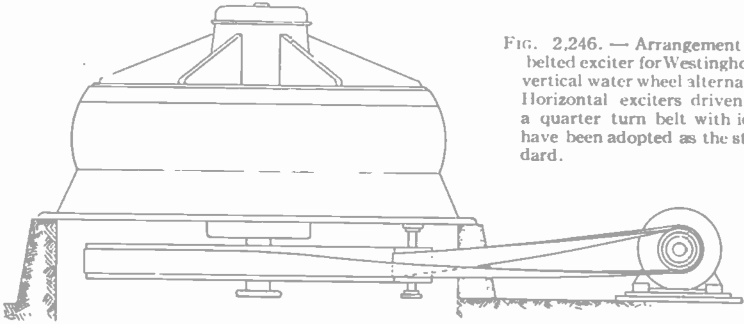


FIG. 2,246. — Arrangement of belted exciter for Westinghouse vertical water wheel alternator. Horizontal exciters driven by a quarter turn belt with idler have been adopted as the standard.

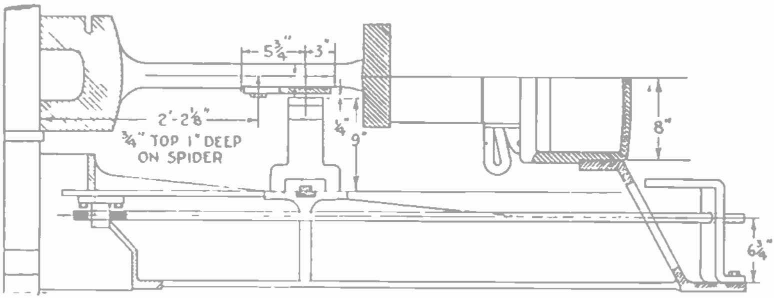


FIG. 2,247.—Arrangement of hand operated brake of Westinghouse vertical water wheel alternator. The brake shoes are supported on pads cast on the lower guide bearing bracket arms and have the operating rod extending to a hand wheel outside of the alternator frame.

engine are decidedly unlike, the principle of operation of the high speed turbine driven alternator does not differ from that of alternators designed for being driven by other types of engine or by water wheels. There are, therefore, with the turbine driven alternator no new ideas for the operator who is familiar with the older forms to acquire.

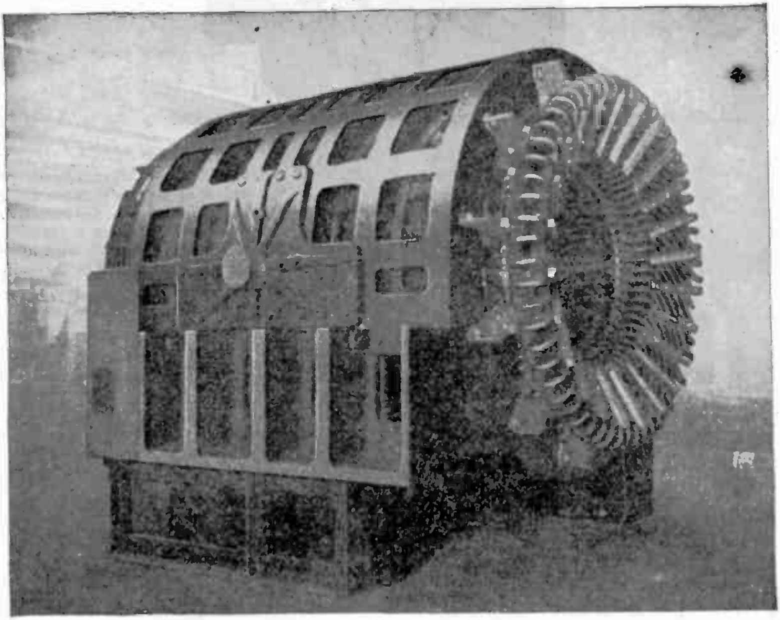


FIG. 2,248.—Westinghouse turbine alternator completely wound showing coil bracing, trunnions and feet.

It must be obvious that the proportions of such extra high speed machines must be very different from those permissible in alternators of much slower speeds.

Ques. How does a turbine rotor differ from the ordinary construction?

Ans. It is made very small in diameter and unusually long.

Ques. Why?

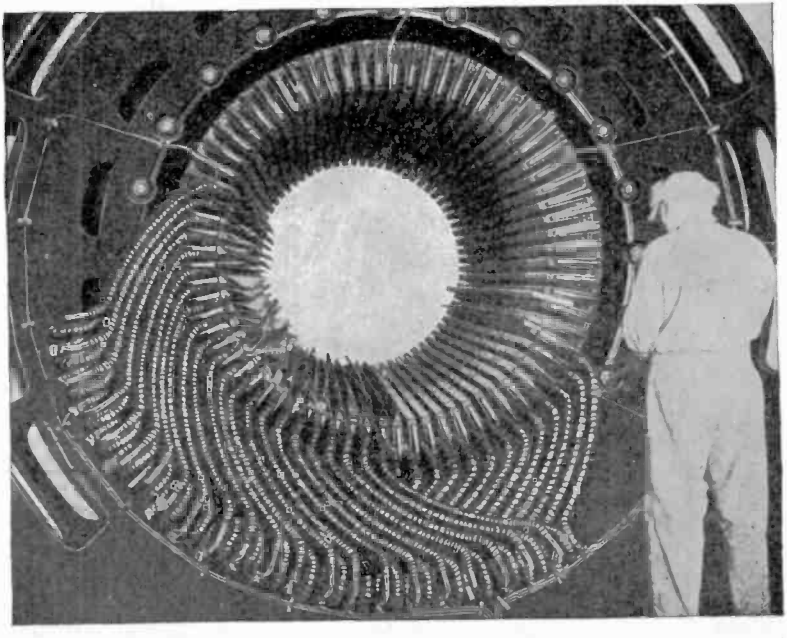


FIG. 2,249.—Stationary armature of Westinghouse turbine alternator with part of the winding in place. Because of the small number of coils in a turbine alternator as compared with a slow speed machine of the same *kva*. rating, each coil carries a great amount of power on large load, particularly at times of short circuits or grounds on the external circuit. The "throw" of the coils is large, leaving a considerable part of the winding in the end turns unsupported by the armature core. For these reasons great stresses, which are dangerous, if effective means be not adopted to withstand them, may exist between the coils. The inductors are of such cross section that they can be made rigid and insulated satisfactorily. The end turns are given a fan like form as shown, affording ventilation and effective bracing as shown in fig. 2,248. Cord lashings are, except in the smallest frames, used only for holding in the small spacing blocks between the coils. They are not depended on to support the coils. Malleable iron braces, hard maple blocks, and brass or steel bolts with brass washers are used to withstand the mechanical stresses imposed on the armature coils by external short circuits.

Ans. To reduce vibration and centrifugal stresses.

Ques. What are the two classes of turbine driven alternators?

Ans. They are classed as vertical or horizontal.

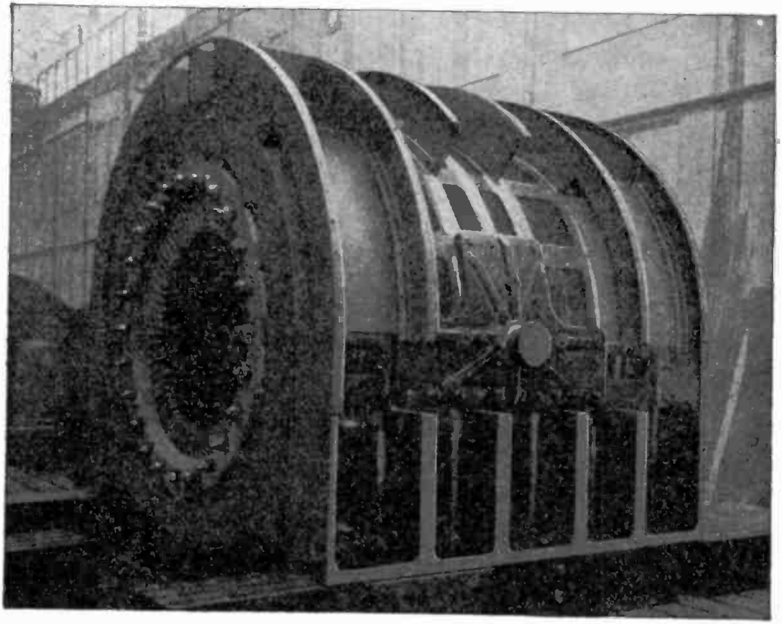


FIG. 2,250.—Westinghouse turbine alternator skeletonized frame with punchings, trunnions, feet and superstructure attached.

Ques. How do they compare?

Ans. The vertical type requires less floor space than the horizontal design, and while a step bearing is necessary to carry the weight of the moving element, there is very little friction in the main bearings.

The horizontal machine, while it occupies more space, does not require a step bearing.

Ques. Describe a step bearing.

Ans. It consists of two cylindrical cast iron plates bearing upon each other and having a central recess between them into which lubricating oil is forced under considerable pressure by a steam or electrically driven pump, the oil passing up from beneath.

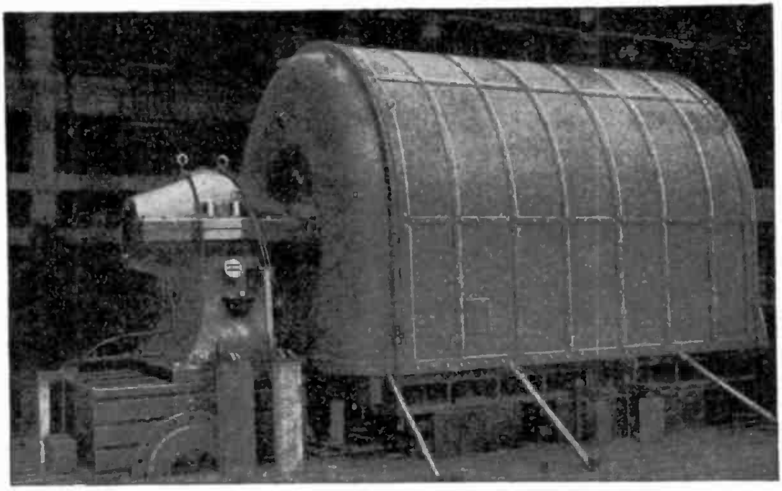
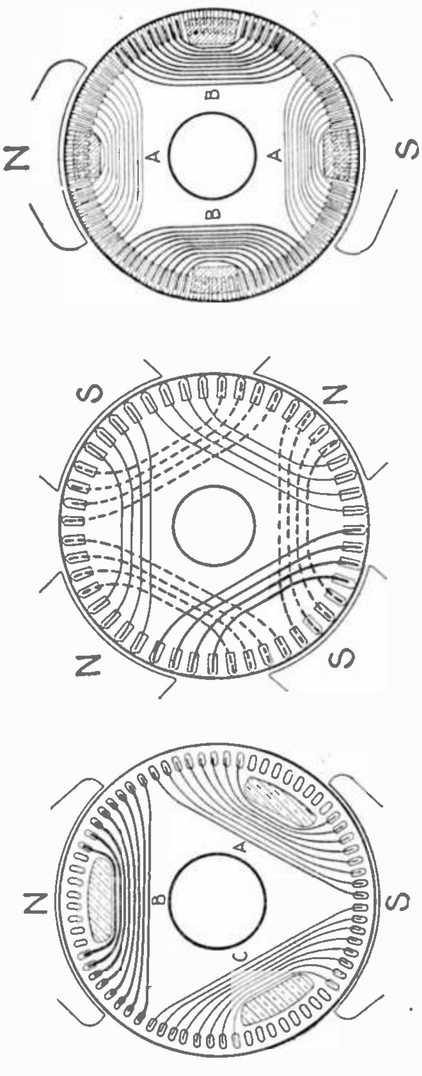


FIG. 2,251.—Westinghouse turbine alternator, view showing machine with SK frame completely assembled for testing revolving elements.

Ques. What auxiliary is generally used in connection with a step bearing?

Ans. A weighted accumulator is sometimes installed in connection with the oil pipe as a convenient device for governing the step bearing pumps, and also as a safety device in case the pumps fail.



FIGS. 2,252 to 2,254.—Diagram of turbine alternator windings for revolving armature. Fig. 2,252 illustrates a two pole design in which all overlapping is avoided. It has 72 slots of which only 48 are filled, giving 8 slots per phase. The projecting claws from the brass end shield which hold the coils in position are shown in section. Fig. 2,253 shows a four pole design having 48 slots or 4 slots per phase per pole, the coils being made up of 8 inductors per slot taped together, the end bends forming two ranges. Fig. 2,254 shows a two phase armature with 18 slots per pole per phase. The core discs are spaced out as for 108 slots, but of these, 4 lots of 7 each are not stamped out, and 8 of those stamped are left empty, so that there are 72 slots filled. Present practice employs a stationary instead of revolving armature.

Alternators of Exceptional Character.—There are a few types of alternator less frequently encountered than those already described. The essentials of such machines are here briefly given.

Asynchronous Alternators.—In these machines, the rotating magnet which, with definite poles, is replaced by a rotor having closed circuits. In general construction, they are similar to asynchronous induction motors having short circuited rotors; for these alternators, when operating as motors, run at a speed slightly below synchronism and act as alternators when the speed is increased above that of synchronism. Machines of this class are not self-exciting, but require an alternating or polyphase current previously supplied to the mains to which the stationary armature is connected.

Asynchronous alternators may be advantageously used in central stations that may be required to sustain a very sudden increase of load. In such cases, one or more asynchronous machines might be kept in operation as a non-loaded motor at a speed just below synchronism until its output as an alternator is required; when by merely increasing the speed of the engine it will be made to act as an alternator, thus avoiding the delays usually occurring before switching in a new alternator.

Image Current Alternators.—When the generated frequency of alternators excited by low frequency currents is either the sum or the difference of the excitation and rotation frequencies, any load current flowing through the armature of the machine is exacty reproduced in its field circuit. These reproduced currents are characteristic of all types of asynchronous machines, and are called "image currents," as they are actually the reflection from the load currents delivered by the armature circuit.

As the exciter of a machine of this type carries "*image currents*" proportional to the generated currents, its size must be proportional to the capacity of the machine multiplied by the ratio of the excitation and generated frequencies; therefore, in the commercial machines, the excitation frequency is reduced to the minimum value possible; from two to five cycles per second being suitable for convenient employment.

These machines as heretofore constructed are not self-exciting, but as the principle of image current enables the construction of self-exciting alternators, it will be of advantage to have a general understanding of the separately excited machine under different conditions of excitation.

When the generated frequency of the machine is equal to the difference of the excitation and rotation frequencies, the magnetization of the machine is higher under a non-inductive load than under no load. This is principally due to the ohmic resistance of the field circuit, which prevents the image current entirely neutralizing the magnetomotive force of the armature current. In other words, the result of the magnetomotive force of the armature and image currents not only tends to increase the no load magnetization of the machine at non-inductive load, but depresses the original magnetization at inductive load, so that the terminal voltage of the machine increases with non-inductive load, and decreases with inductive load.

Again, the generated frequency is equal to the sum of the excitation and rotation frequencies, the resistance of the field circuit reacts positively; that is, it tends to decrease the magnetization, and consequently the terminal voltage of the machine at both inductive and non-inductive loads.

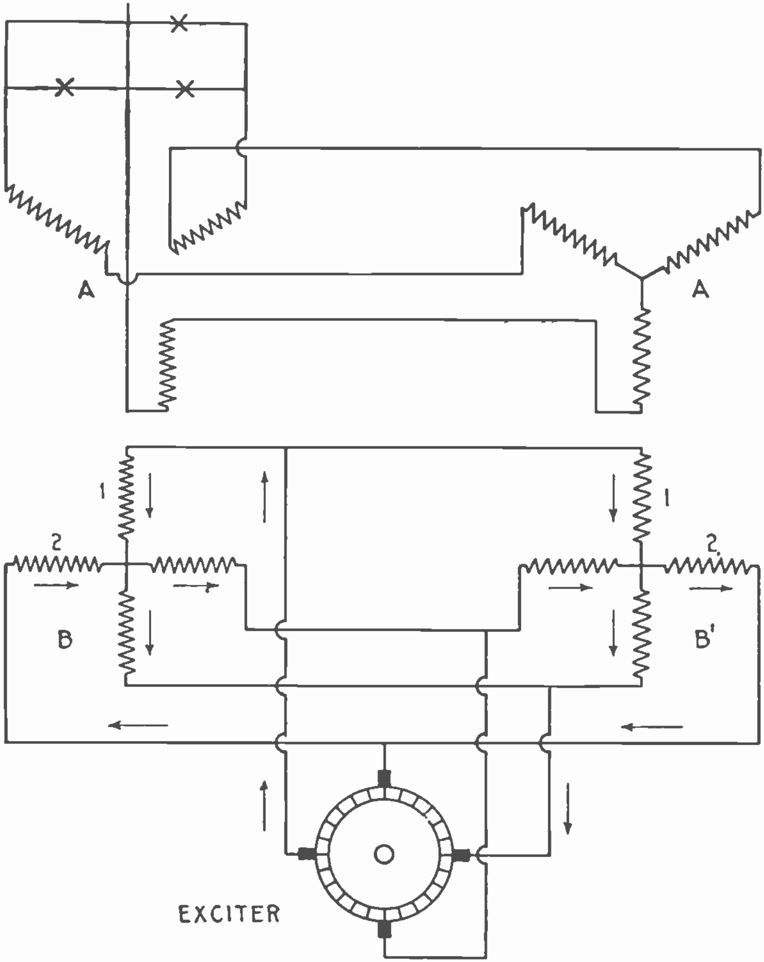


FIG. 2,255.—Diagram of constant pressure image current alternator connections. The image or reproduced currents are characteristic of all types of asynchronous machines, and are called image currents because they are actually the reflection from the load currents delivered by the armature circuit. The principle of operation is explained in the accompanying text.

In the constant pressure machine, the two effects are combined and opposed to one another.

The connections of two alternators with diphase excitation are shown by fig. 2,255.

Extra High Frequency Alternators.—Alternators generating currents having a frequency up to 10,000 or 15,000 cycles per second have been proposed several times for special purposes, such as high frequency experiments, etc. In 1902 Nikola Tesla proposed some forms of alternators having a large number of small poles, which would generate currents up to a frequency of 15,000 cycles per second.

Later, the Westinghouse Company constructed an experimental machine of the inductor alternator type for generating currents having a frequency of 10,000 cycles per second. This machine was designed by Samms. It

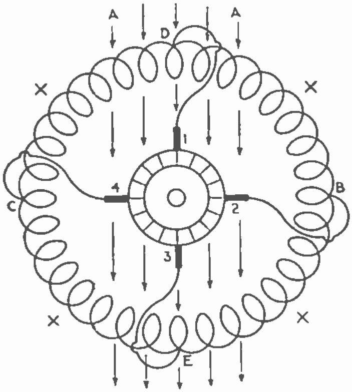


FIG. 2,256.—Diagram of connections of self-exciting image current alternator.

had 200 polar projections with a pole pitch of only 0.25 inch, and a peripheral speed of 25,000 feet per minute. The armature core was built up of steel ribbon 2 inches wide and 3 mils thick. The armature had 400 slots with one wire per slot, and a bore of about 25 inches. The air gap was only 0.03125 inch. On constant excitation the voltage dropped from 150 volts at no-load to 123 volts with an output of 8 amperes.

Self-Exciting Image Current Alternators.—The type of machine described in the preceding paragraph can be made self-exciting by connecting each pair of brushes, which collect the current from the armature, with a field coil so located that the flux it produces will be displaced by a pre-determined angle depending on the number of phases required, as shown by fig. 2,256. The direction of the residual magnetism of the machine is shown by the arrows A, A.

When the armature is rotated, a pressure will be generated between the brushes 2 and 4, and a current will flow from C, through the coils XX, to B, producing a flux through the armature at right angles to the residual magnetism and establishing a resultant magnetic field between D, B, and D, C. This field will generate a pressure between the brushes 1 and 3, and a current will flow D, through XX, to E, in such a direction that it will at first be opposed to the residual magnetism, and afterward reverse the direction of the latter. At the moment the residual magnetism becomes zero, the only magnetism left in the machine will be due to the currents from the brushes 2 and 4, and their field combining with the vertical reversed field will produce a resultant polar line between B and E. As these operations are cyclic, they will recur at periodic intervals, and the phenomena will become continuous. The negative field thus set up in the air gap of the machine will cut the conductors of the stator and will be cut by the conductors of the rotor in such a manner that the voltages generated between the brushes of the armature will be equal and opposite to those between the terminals of the stator.

TEST QUESTIONS

1. *For what service are alternators adapted?*
2. *Give a classification of alternators.*
3. *What are the essential features of a single phase alternator?*
4. *In actual machines, why must the magnet cores be spaced out around the armature with considerable distance between them?*
5. *Is there any gain in making the width of the armature coils any greater than the pole pitch, and why?*
6. *Define a polyphase alternator and what is its use?*
7. *What is the difficulty encountered in starting a motor with single phase current?*

8. *In what type machine are six phase and twelve phase windings used?*
9. *Upon what does the choice of belt driven or direct connected alternators depend?*
10. *What provision should be made in the design of an alternator to adapt it to belt drive?*
11. *Give a rule for obtaining the proper size of belt to deliver a given horse power.*
12. *What are some of the objections to chain drive?*
13. *What is the difference between a direct connected and a direct coupled unit?*
14. *When is the revolving type of armature used, and why?*
15. *Could a dynamo be converted into an alternator?*
16. *What is the nature of motion?*
17. *What are the advantages of revolving field alternators?*
18. *Explain the essential features of a revolving field alternator.*
19. *What is an inductor alternator?*
20. *What influence have the inductors on the field flux?*
21. *Name two classes of inductor alternators.*
22. *State a disadvantage of inductor alternators.*
23. *For what service are inductor alternators adapted?*
24. *Define the term* hunting or singing *in alternators.*
25. *What is a monocyclic alternator?*
26. *What is an amortisseur winding used for?*
27. *What is a teaser coil?*
28. *Define armature reaction.*

29. *Explain how the field becomes distorted by armature reaction.*
30. *Explain how the field becomes weakened by armature reaction.*
31. *In what kind of armature is the weakening by armature reaction especially pronounced?*
32. *What would be the effect if the current lead the pressure?*
33. *Describe single phase, and three phase reaction.*
34. *Draw diagrams illustrating super-position of fields.*
35. *Define magnetic leakage and what causes it.*
36. *In what ways are the fields of alternators excited?*
37. *What is a self-excited alternator?*
38. *What are the advantages of gear driven exciters?*
39. *How is a fly wheel alternator constructed?*
40. *What are the features of water wheel alternators?*
41. *How does a turbine armature differ from the ordinary construction, and why?*
42. *Name two classes of turbine alternators.*
43. *Describe a step bearing.*
44. *Describe some alternators of exceptional character.*

CHAPTER 51

Construction of Alternators

The construction of alternators follows much the same lines as dynamos, especially in the case of machines of the revolving armature type. Usually, however, more poles are provided than on direct current machines, in order to obtain the required frequency without being driven at excessive speed.

The essential parts of an alternator are:

1. Field magnets;
2. Armature;
3. Collector, or slip rings;

and in actual construction, in order that these necessary parts may be retained in proper co-relation, and the machine operate properly there must also be included:

4. Frame;
5. Bed plate;
6. Pulley.

Field Magnets.—The early forms of alternator were built with permanently magnetized steel magnets, but these were later discarded for electro-magnets.

Alternators are built with three kinds of electro-magnets, classed according to the manner in which they are excited, the machines being known as:

1. Self-excited;
2. Separately excited;
3. Compositely excited.

Ques. What is a self-excited alternator?

Ans. One in which the field magnets are excited by current from one or more of the armature coils, or from a separate winding (small in comparison with the main winding), the cur-

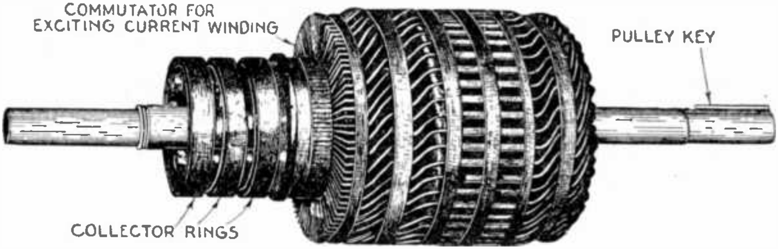


FIG. 2,257.—General Electric armature for self-excited alternator. There are two independent windings, one for the main current, and one for the exciting current. The winding for the latter current occupies a very small amount of space, and is placed in the slots on top the main winding. The commutator to which the exciter winding is connected, is located between the collector rings and the core. It is of standard construction with end clamps holding the bars in place on the insulated commutator drum. The armature coils are form wound and the core is built of sheet steel laminations, annealed and japanned to prevent hysteresis and eddy current losses. Ventilated openings are provided to allow a free circulation of air both around the ends of the windings and through ducts in the laminated core. The core is clamped by bolts between the flanges of the armature spider which is keyed to the shaft. These flanges have cylindrical extensions with ribbed surfaces, which form a support for the ends of the armature coils. The ribbed surfaces form air passages from the core outward around the ends of the coils, thus ventilating both core and coils.

rent being transformed into direct current by passing it through a commutator.

Fig. 2,257 shows an armature of a self-excited machine, the exciting current being generated in a separate winding and passed through a commutator.

Ques. For what class of service are self-exciting alternators used?

Ans. They are employed in small power plants and isolated lighting plants where inductive loads are encountered.

Ques. What is a separately excited alternator?

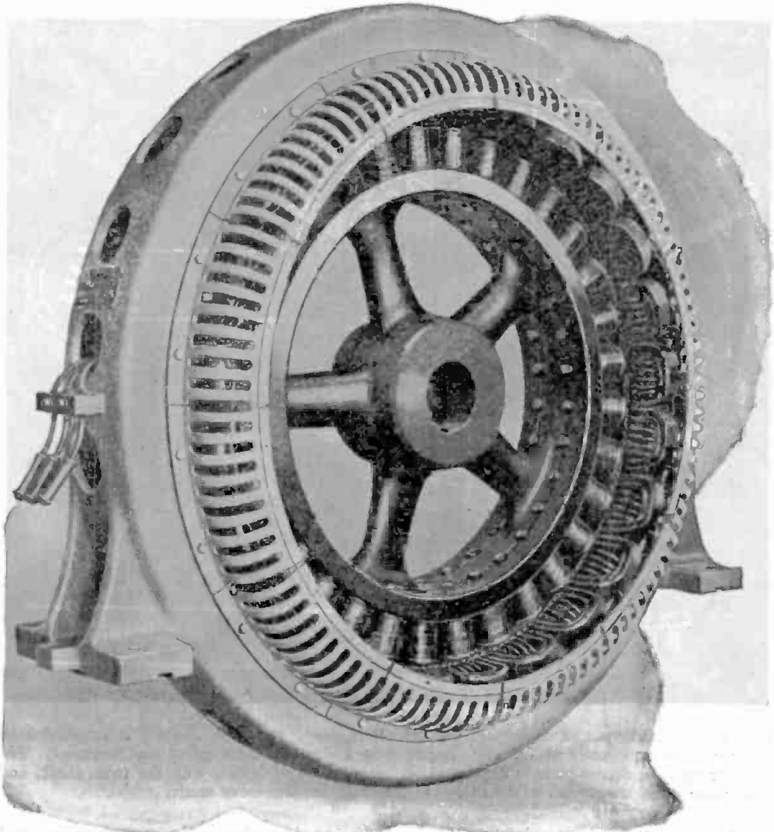


FIG. 2,258.—Allis Chalmers 187½ *kva.*, 225 *r.p.m.*, 60 cycle engine driven alternator.

Ans. One in which the field magnets are excited from a small dynamo independently driven or driven by the alternator shaft, either direct connected or by belt as shown in fig. 2,259.

Ques. What is a compositely excited alternator?

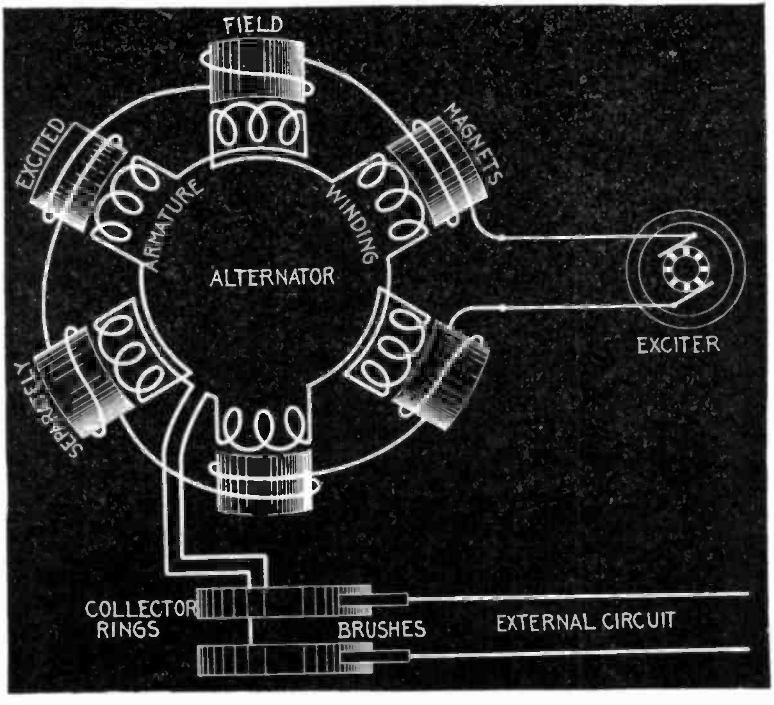


FIG. 2,259.—Diagram of separately excited alternator. The field winding is supplied with direct current, usually at 125 volts pressure by a small dynamo called the "exciter." The latter may be driven by independent power, or by belt connection with the main shaft, and in some cases the exciter is directly connected to the alternator shaft.

Ans. A composite alternator is similar to a compound wound dynamo in that it has two field windings.

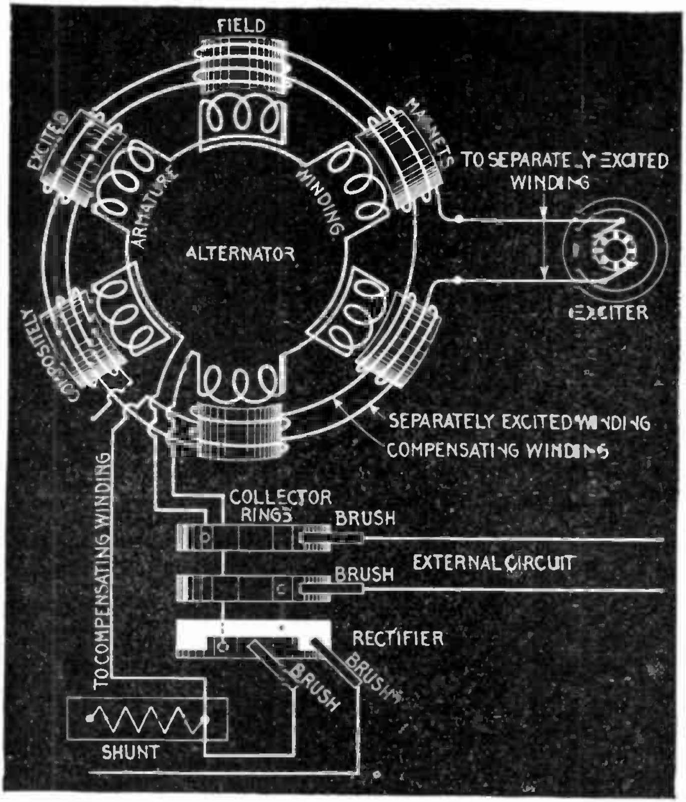


FIG. 2,260.—Diagram of compositely excited alternator. The current for exciting the field magnets is obtained, partly from an exciter and partly from the windings of the alternator, being transformed into direct current by the rectifier. The connections are as shown. One end of the armature winding is connected to one of the collector rings; the other end, to the solid black part of the rectifier, as shown, the white part of the rectifier being connected to the other collector ring. Two brushes bear on adjacent teeth of the rectifier and are connected to the compensating winding circuit across which is a shunt. These connections are shown more clearly in fig. 2,261. ***In operation*** the separately excited coils set up the magnetism necessary for the generation of the voltage at no load. The main current coming from the armature is shunted, part going through the shunts and the remainder around the compensating winding, furnishing the additional magnetism necessary to supply the voltage to overcome the armature impedance. As shown, both field windings encircle every pole, but in some machines the rectified current will traverse a few poles only, the current from the exciter traversing the remainder.

In addition to the regular field coils which carry the main magnetizing current from the exciter, there is a second winding upon two or upon all of the pole pieces, carrying a rectified current from the alternator which strengthens the field to balance the losses in the machine, and also if so desired, the losses on the line as shown in fig. 2,260.

Ques. What is a magneto?

Ans. A special form of alternator having permanent magnets

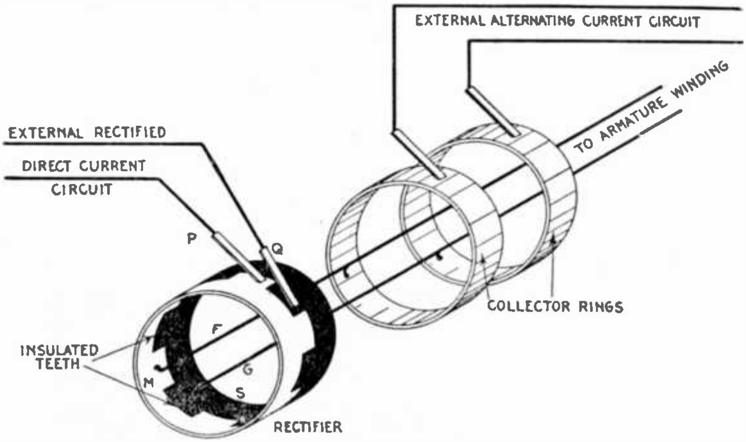


FIG. 2,261.—Diagram showing construction of rectifier and connections of compositely excited alternator. The rectifier consists of two castings M and S, with teeth which fit together as shown, being insulated so they do not come in contact with each other. Every alternate tooth being of the same casting is connected together, the same as though joined by a conducting wire. There are as many teeth as there are poles. One end of the armature winding is connected direct to one of the collector rings, while the other is connected to M, of the rectifier, the circuit being through brushes P and Q, the shunt, and compensating winding to the other collector ring. The brushes P and Q, contact with adjacent teeth, when one is in contact with the solid black casting the other touches the light casting. The principle of action is the same as a commutator, briefly: to reverse the connections terminating at the brushes P and Q, in synchronism with the reversals of the alternating current induced in the armature winding, thus obtaining direct current for the compensating field winding. The shunt resistance placed across the compensating winding circuit permits adjusting the compounding of the machine to the circuit on which it is to work, since by varying the resistance the percentage of the total current passing through the compensating winding can be changed. It will be seen by tracing the path of the current for each direction in the armature winding that while the rectifier causes the current to flow in the same direction in the compensating field winding, it still remains alternating in the external circuit.

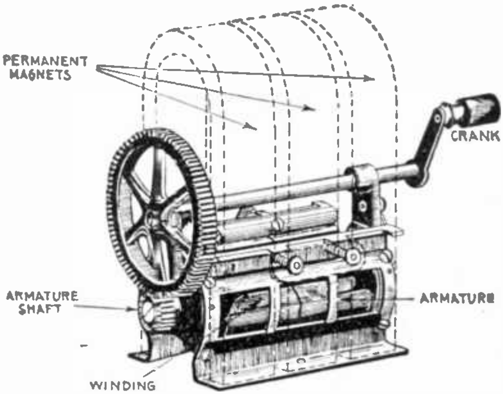
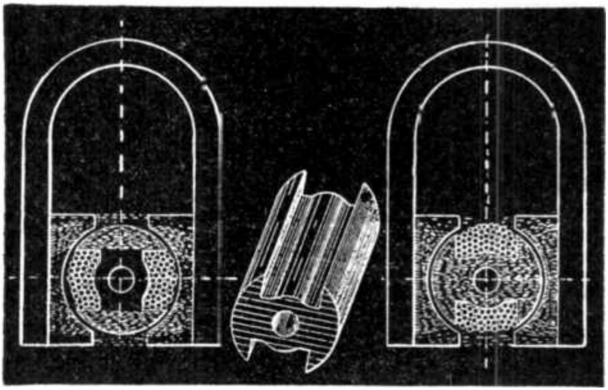


FIG. 2,262.—Connecticut magneto; view showing permanent magnets in dotted lines. *It consists of* three permanent U shape magnets, between the poles of which is a shuttle type armature. The latter is geared to a hand crank in sufficient velocity ratio to give the desired speed without too rapid turning of the crank. This type of magneto is used to generate current for operation of telephone call bells.

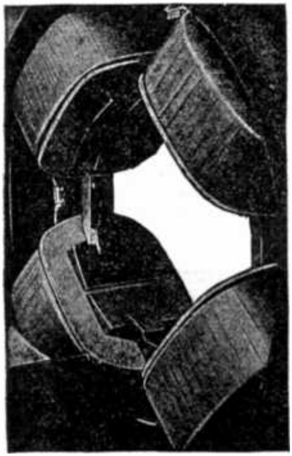


FIGS. 2,263 to 2,265.—Diagram illustrating the operation of a magneto. The shuttle shaped armature is wound from end to end with insulated wire, so that when rotated, a powerful alternating current is produced in the winding by cutting the magnetic lines, whose varying strength is shown by the shaded portions in the two views. When in the position shown in the first diagram, the lines of force mostly converge at the top and bottom, finding a direct path through the metal end flanges of the shuttle. When in the position shown in the second diagram, the lines are converged so as to pass through the armature core. Fig. 2,264 shows detail of the armature core.

for its field, and used chiefly to furnish current for gas engine ignition and for telephone call bells.

Details of construction and operation are shown in figs. 2,262 to 2,265.

Ques. What are the two principal types of field magnet?



Ans. Stationary and revolving.

Ques. What is a common construction of stationary field magnets?

Ans. Laminated pole pieces are used, each pole being made up of a number of steel stampings riveted together and bolted or preferably cast into the frame of the machine. The field coils are machine wound and carefully insulated. After winding they are taped to protect them from mechanical injury. Each coil is then dipped in an insulating compound and afterwards baked to render it impervious to moisture.

FIG. 2,266.—Stationary field of General Electric multiphase revolving armature alternator; view showing brass grids on pole pieces for synchronous motor operation. When designed for this use the machine is provided with amortisseur winding on the poles. As shown in the illustration this winding consists of a brass collar around the pole tip with a cross rib integral with the collar, fitting in a slot in the pole face parallel with the shaft. This construction assists in bringing the machine up to synchronous speed as an induction motor, ordinarily checks any tendency toward hunting and does not in any way affect the operation of the machine as an alternator. The main field winding should be connected through switches in the field frame in order that the field circuit may be broken up to eliminate any danger that might arise from induced voltage. It is not advisable to throw on a full rated voltage and a compensator should, therefore, be provided to reduce the pressure.

Ques. Describe the construction of a revolving field.

Ans. The entire structure or field consists of a shaft, hub or spider, field magnets and slip rings. The magnet poles consist of laminated iron stampings clamped in place by means

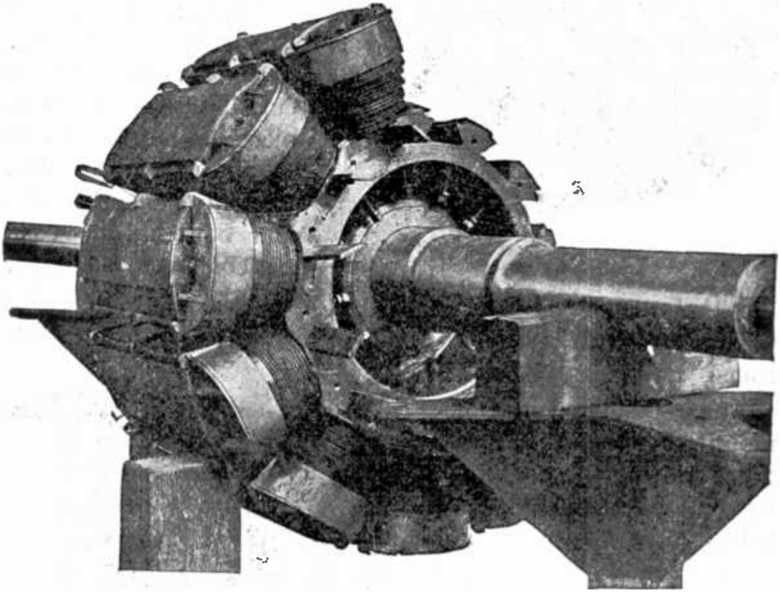


FIG. 2,267.—Wagner revolving field of 300 kilowatt alternator during construction, illustrating the method of attaching the field magnets to the hub by dovetail joints. After the notched ends of the pole pieces are pushed into the grooves in the hub, tapered keys, which are plainly seen, are driven in, thus making a tight joint which will not shake loose.

of through bolts which, acting through the agency of steel end plates, force the laminated stampings into a uniform, rigid mass. This mass is magnetically sub-divided into so many small parts that the heating effect of eddy currents is reduced to a minimum. The cores are mounted upon a hub or spider either by dovetail construction or by means of through bolts, so as to resist the centrifugal force which they must withstand in operation, either method permitting the easy removal of any particular field pole if necessary. The field coils are secured upon the pole pieces either by horns in one piece with the laminations, or separate and bolted. The coils are connected in series, cable leads connecting them to slip rings placed on the shaft.

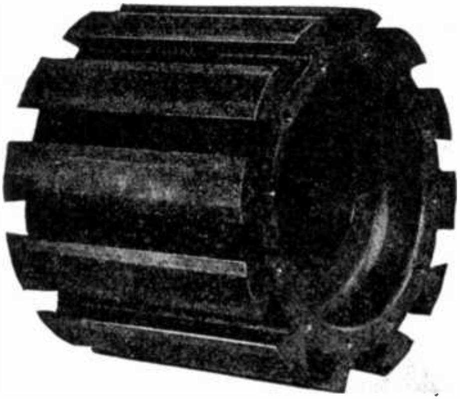


FIG. 2,268.—Wagner cast steel hub with dovetail grooves for attaching the revolving field magnets. Such construction is generally used on machines of small and medium size.

Ques. What are slip rings?

Ans. Insulated rings mounted upon the alternator shaft to receive direct current for the revolving field.*

In construction provision is made for attaching the field winding leads. The rings are usually made of cast iron and are supported mechanically upon the shaft, but are insulated from it and from one another.

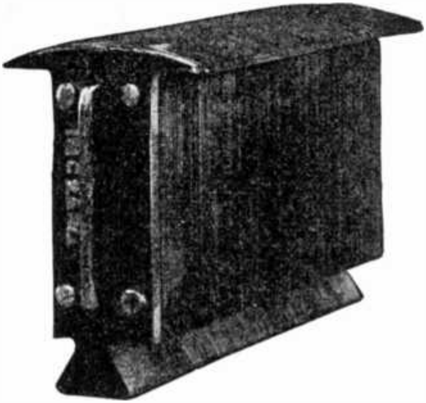


FIG. 2,269.—Wagner laminated pole piece with horns stamped in one piece. The laminations are held together between two end pieces by through rivets, as shown.

*NOTE.—The author objects to the indiscriminate use of the terms *slip rings* and *collector rings*. ***As distinguished*** from slip rings, collector rings "collect" the alternating currents induced in an alternator of the revolving armature type. ***Evidently*** slip rings "collect" nothing but deliver direct current to a revolving field.

The current is introduced by means of brushes as with a commutator. Carbon brushes are generally used.

A good design of slip ring should provide for air circulation underneath and between the rings.

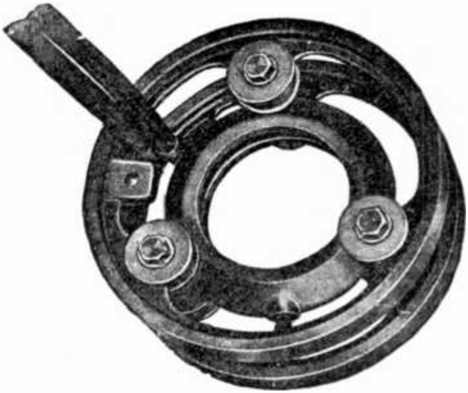


FIG. 2,270.—General Electric slip rings; view showing construction and attachment of cable leads to field winding. They are so designed that all surfaces of the rings have easy access to the air, in order to obtain good ventilation.

FIG. 2,271.—General Electric field coil showing one method of winding. The field coils on the larger machines consist of a single strip of flat copper, wound on edge as shown, so that the surface of every turn is exposed to the air for cooling. The flat sides of the copper strip rest against each other and the entire coil forms a structure of great solidity which can be easily removed for inspection and repair.

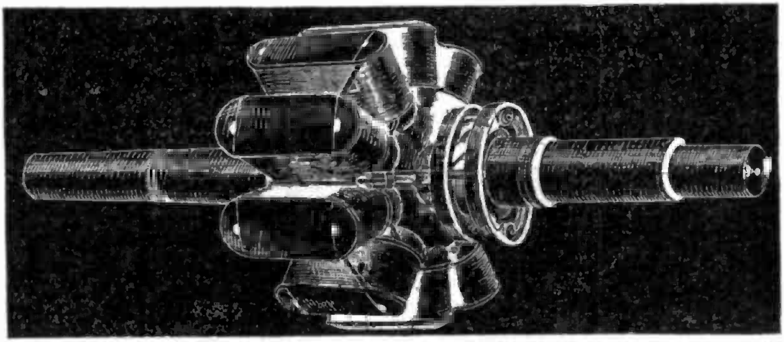


FIG. 2,272—Revolving field of General Electric 10 pole alternator. ***In construction,*** the cores of the field poles are built up from punchings of laminated steel, and assembled under considerable pressure between malleable iron or steel end plates and riveted together. Substantial insulation is placed on the pole cores and over this is wound the field coils of cotton covered wire. After the wire is in place, the completed poles are baked to expel any moisture and are then treated with insulating varnish. They are then assembled on a laminated spider, being held in place by dovetail joints made tight by the use of taper keys. Special casting plates are finally fastened in place over the dovetails effectually closing them. The assembly of the field is completed by the insertion of the shaft into the field spider under heavy hydraulic pressure. All the coils are connected in series, cable leads connecting them to slip rings placed on the shaft. Each slip ring is provided with a double type brush holder, making it possible to clean brushes while the alternator is in service, by simply removing one brush at a time.

FIG. 2,273.—General Electric field coil, showing another method of winding. In the smaller machines the wire is wound on spools which are slipped over the pole pieces, the latter being built of sheet iron, spreading at the pole face so as to secure not only a wide polar arc for the proper distribution of the magnetic flux, but also to hold the field winding in place.

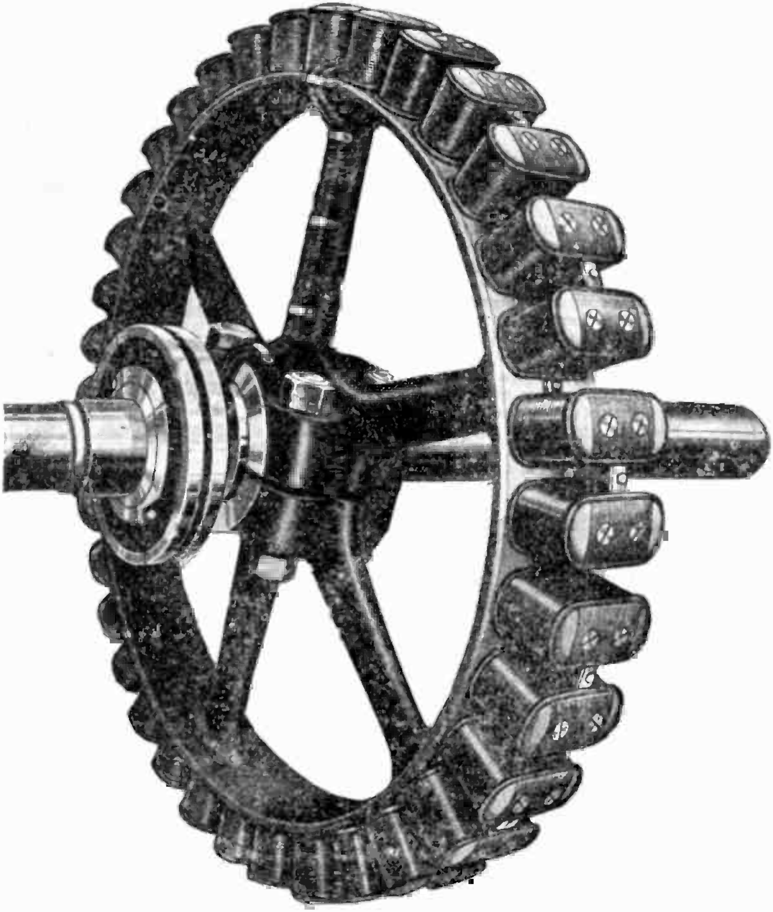


Fig. 2,274.—Triumph 36 pole fly wheel type revolving field. The spider has the form of a fly wheel having spokes and rim to which the field magnets are attached by through bolts. The field coils are of copper strap bent on end, the kind generally used on large machines. The series connection of the coils is plainly shown, also the two cables leading via one of the spokes to the slip rings.

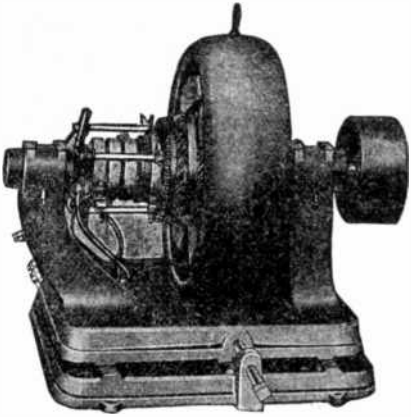


FIG. 2,275.—General Electric multi-phase revolving armature alternator, designed for use in small power plants and isolated lighting plants where inductive loads are encountered. Built for pressures of 120, 240, 480, and 600 volts. These voltages have been recommended by the American Institute of Electrical Engineers, and will cover the needs of any set of conditions ordinarily met with. These standard voltages not only permit economical distribution, but they are such that no transformers are necessary to reduce the line pressure for ordinary cases. For transmitting power relatively long distances, 600 volts is usually employed. Where there is a demand for 480 volt service, a 480 volt alternator should be selected and if lower voltages be also desired, an auto-transformer may be furnished by means of which 240 volts can be obtained. When 120 volt circuits are necessary for lighting, etc., the 240 volt pressure can be still further reduced to 120 volts by means of another auto-transformer. However, this double reduction will rarely be found necessary.

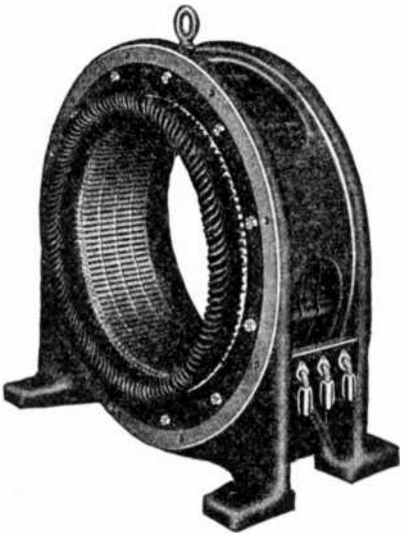
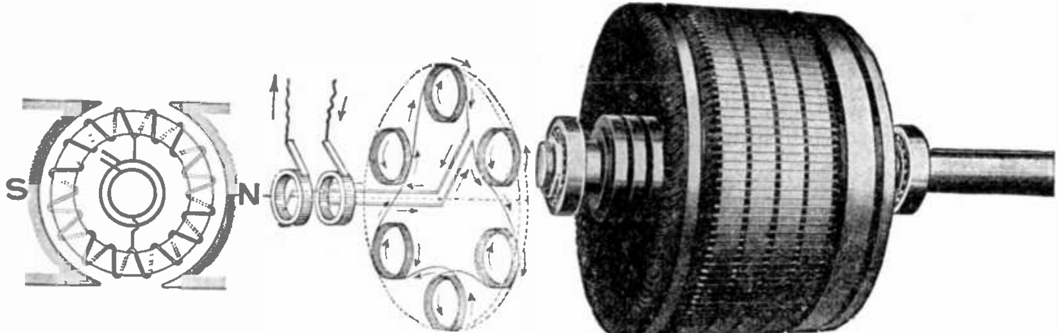


FIG. 2,276.—Graybar stationary armature. In this type of armature, the core upon which the winding is placed, is built into the frame as shown, the core teeth projecting inwardly like internal gear teeth, forming a cylindrical chamber for the revolving field. The core is built up of iron, laminated and japanned to prevent eddy currents and hysteresis losses. The laminations are rigidly bolted between two heavy end plates. The armature coils are of copper bar impregnated with insulating compound. They are held in the slots by wedges which allow their ready removal for inspection or repairs.



Figs. 2,277 to 2,279.—Various types of armature; fig. 2,277 ring armature; fig. 2,278 disc armature; fig. 2,279 drum armature. The latter type is now almost universally used, the others being practically obsolete. A Gramme ring wound and connected to collector rings as in fig. 2,277, will yield an alternating current. In a multipolar field, the ring will need multipolar connections alternated at points corresponding to the pitch of the poles. Fig. 2,278 illustrates the so-called "Siemens" disc armature. The armature coils are arranged around the periphery of a thin disc. The field magnets consist of two crowns of fixed coils, with iron cores arranged so that their free poles are opposite one another. This type was created in 1878 by Herr von Hefner, engineer to Messrs. Siemens and Halske. Fig. 2,279 shows a modern drum armature of a three phase machine. It is similar in appearance to a direct current armature except for the absence of the commutator and its connections. The drum armature is the prevailing type.

Ques. What form of spider is used on large alternators?

Ans. It is practically the same form as a fly wheel.

It consists of hub, spokes, and rim, to which the magnets are bolted. On alternators of the fly wheel type the spider rim is made of sufficient weight to obtain full fly wheel effect, thus making a separate fly wheel unnecessary.

Armatures.—In construction, armatures for alternators are similar to those employed on dynamos; they are in most cases simpler than direct current armatures due to the smaller number of coils, absence of commutator with its multi-connections, etc. Alternator armatures may be classified in several ways:

1. With respect to operation, as
   a. Revolving; *b*. Stationary.

2. With respect to the core, as
   a. Ring; *b*. Disc; *c*. Drum.

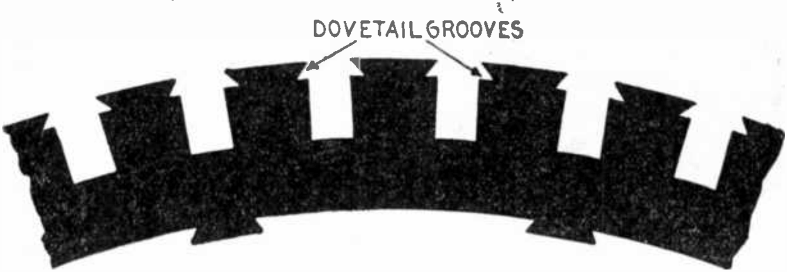


FIG. 2,280.—A style of punching largely used for armature cores. The teeth are provided with dovetail grooves near the circumference. After the coil is inserted in a groove, a wooden wedge is driven in the groove which encloses the coil and secures it firmly in position. This obviates the necessity of bands to resist the centrifugal force acting on the inductors.

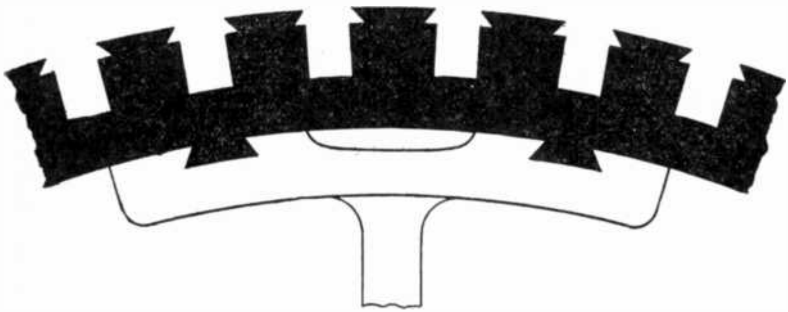


FIG. 2,281.—Large revolving armature construction with segmental punchings dovetailed to spider spokes.

Ring and disc armatures are practically obsolete and need not be further considered. A ring armature has the inherent defect that the copper inside the ring is inactive. Disc armatures were employed by Pacinotti in 1878, and afterwards adopted by Brush in his arc lighting dynamos.

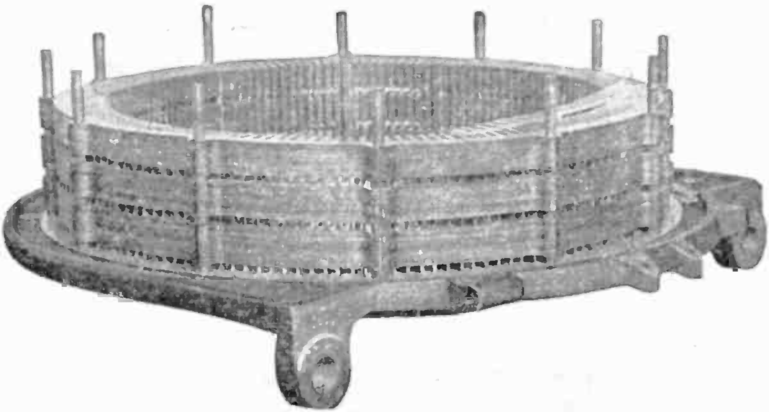


FIG. 2,282.—Elliott engine type alternator armature core being stacked. ***In construction,*** the core is built from punchings of thin transformer steel. Before being stacked the punchings are machine coated with insulating varnish for the purpose of reducing eddy current losses to a minimum. Several air ducts are provided in the core for ventilating purposes. The armature frame consists of two heavy cast iron rings having an I-beam section. The core is clamped securely in position between these rings by bolts which pass through the core but outside of the magnetic circuit. This method of construction gives superior ventilation.

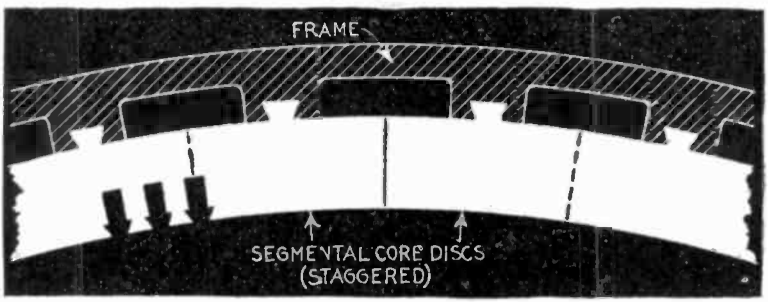


FIG. 2,283.—Construction of large stationary armature; view showing section of core and frame. The core discs are in segments and are attached to the frame by dovetail joints as shown. The joints are staggered in building up the core, that is, they are overlapped so as not to unduly increase the reluctance of the magnetic circuit. Through bolts are seldom used for securing the laminations, because if not insulated, are liable to give rise to eddy currents by short circuiting the discs.

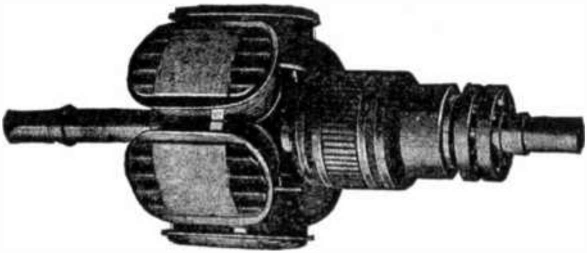


FIG. 2,284.—General Electric revolving field and exciter armature. This is an example of direct connected exciter construction. In this arrangement the armature of the exciter is carried on the alternator shaft at the end farthest from the pulley. In the smaller sizes the magnet frame is bolted to the bearing bracket, but in the larger sizes special construction is used depending upon the conditions to be met. On all alternators of standard design, the field is built for 125 volts excitation and on account of the increased danger from induced voltage, in case the machine is used as a synchronous motor, the builders consider any higher voltage undesirable.

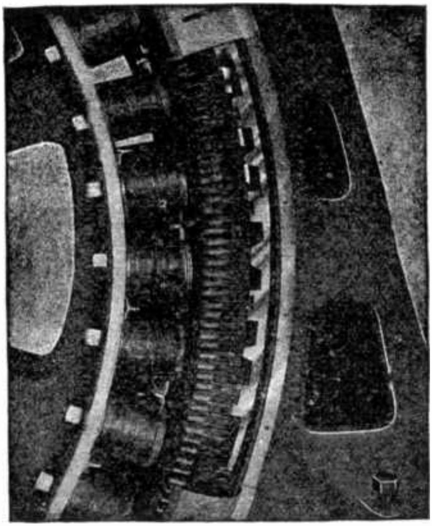


FIG. 2,285.—Section of General Electric alternator showing method of dovetailing core laminations to frame. The latter is made in two general styles, known as the *box type* and *skeleton type*. ***The box type*** consists of a single casting for the smaller sizes, but for large capacity alternators, the frame castings are usually divided into upper and lower sections. ***The skeleton type*** consists of two side castings between which substantial spacing rods are set at

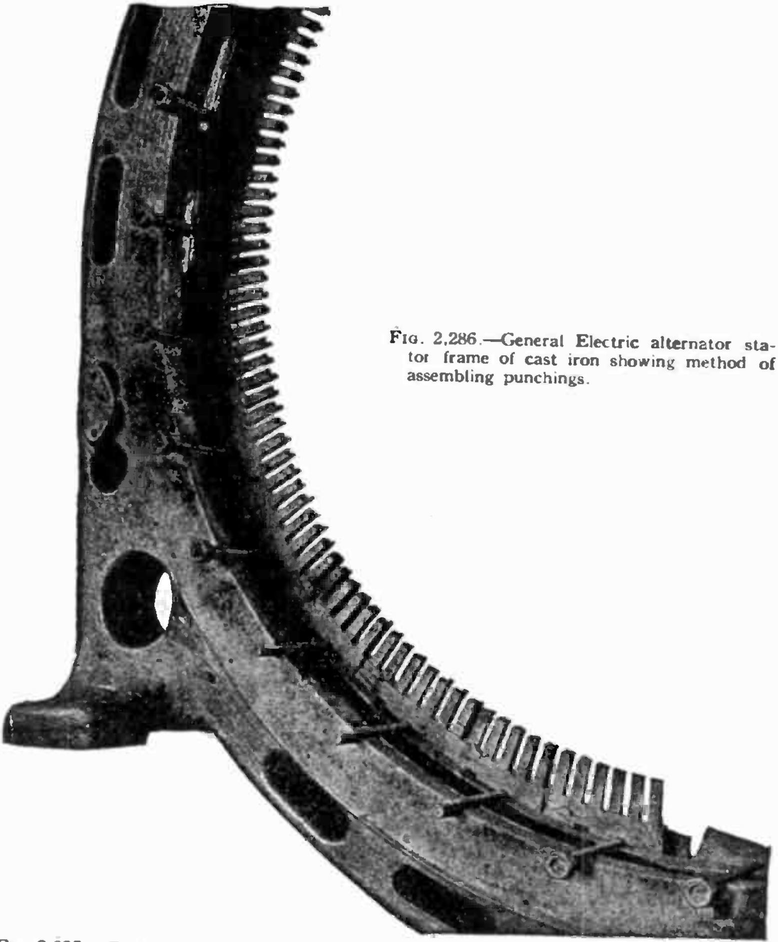
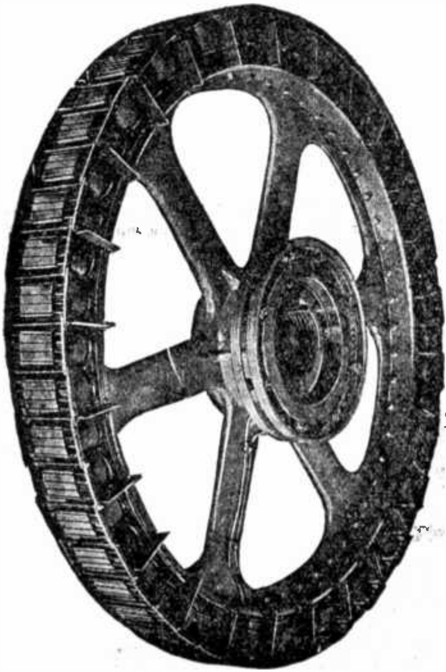


FIG. 2,286.—General Electric alternator stator frame of cast iron showing method of assembling punchings.

FIG. 2,285.—*Text continued.*

regular intervals. The core consists of the usual sheet iron laminations slotted and assembled; they are mounted on the inner periphery of the frame, making lap joints (that is, "staggered" as in fig. 2,283), each section being dovetailed to the frame. Heavy clamping rings or end plates are mounted on both sides of the core by means of bolts, and supporting fingers extend along the slot projections. The design is such as to provide for air circulation.

The design failed for mechanical reasons, but electrically it is, in a sense, an improvement upon the Gramme ring, in that inductors on both sides of the ring are active, these being connected together by circumferential connectors from pole to pole, these corresponding to the end connections on modern drum armatures.



3. With respect to the core surface, as

a. Smooth core;
b. Slotted core.

FIG. 2,287.—Westinghouse engine driven alternator revolving field showing method of supplying collector rings to spider.

In early dynamos the armature windings were placed upon an iron core with a smooth surface. A chief disadvantage of this arrangement is that the magnetic drag comes upon the inductors and tends to displace them around the armature. To prevent this, projecting metal pieces called *driving horns* were fixed into the core so as to take the pressure, but they proved unsatisfactory. This defect together with the long air gap necessary in smooth core construction resulted in the type being displaced by slotted core armatures.

A slotted core is one whose surface is provided with slots or teeth which carry the inductors, as shown in the accompanying illustrations, and is the type almost universally used. The inductors are laid in the slots, the sides and bottoms of which are first carefully insulated by troughs of mica-canvas, micanite or other suitable insulating material.

Ques. What are the advantages of slotted core armatures?

Ans. The teeth protect the inductors, retain them in place against the electrical drag and centrifugal force, and the construction permits a reduction of air gap to a minimum, thus reducing the amount of copper required for the field.

Windings.—Owing to the amount of space required to properly present this subject, it is thought best to devote a separate chapter to it.

TEST QUESTIONS

1. *What are the three essential parts of an alternator?*
2. *What three ways are the field magnets excited?*
3. *What is a self-excited alternator?*
4. *For what class of service are self-exciting alternators used?*
5. *What is a separately excited alternator?*
6. *What is a compositely excited alternator?*
7. *What is a magneto?*
8. *What are the two principal types of field magnet?*
9. *What is the usual construction of stationary field magnets?*

10. *Describe the construction of a revolving field:*
11. *What are slip rings?*
12. *What form of spider is used on large alternators?*
13. *How are armatures classified; 1, with respect to operation; 2, with respect to the core; 3, with respect to the core surface?*
14. *Which is the prevailing type of armature?*
15. *What are the advantages of slotted core armatures?*

CHAPTER 52

Transformers

The developments in the field of electrical engineering which have rendered feasible the transmission of high pressure currents over long distances, together with the reliability and efficiency of modern generating units, have resulted in notable economies in the generation and distribution of electric current.

This has been accomplished largely by the use of distant water power or the centralization of the generating plants of a large territory in a single power station.

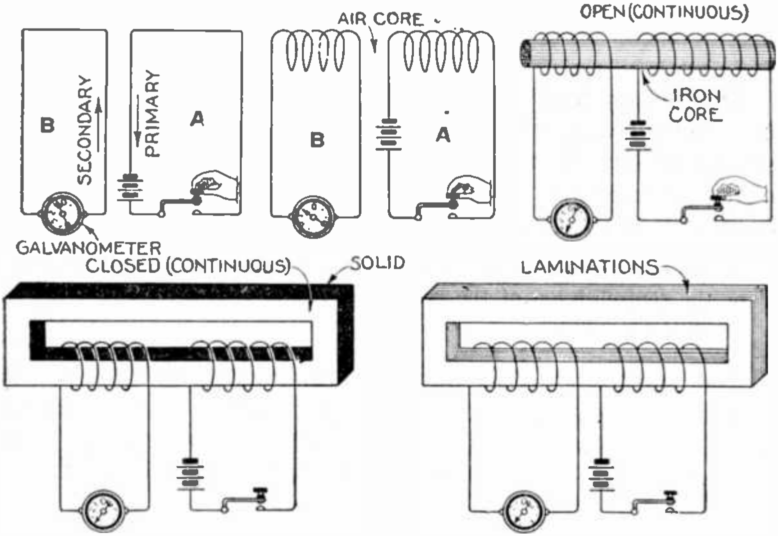
The transformer is one of the essential factors in effecting the economical distribution of electric energy, and may be defined as *an apparatus used for changing the voltage and current of an alternating circuit*. A transformer consists essentially of:

1. A primary winding;
2. A secondary winding;
3. An iron core.

NOTE.—***Michael Faraday*** in 1831 announced the discovery of the theory of electric magnetic induction. Many experiments were made in the following years by ***Henry Masson, Wright*** and others. ***Varley*** in 1856 described his induction coil with a closed magnetic circuit consisting of a bundle of wires with ends bent back on the outside of the copper coil. This was the nearest approach to the laminated core of the modern transformers. A little later ***Zipernowski, Deri*** and ***Blately*** did some very important work on transformers and alternating current distribution which was of a practical and commercial value. During this period American engineers entered the field and contributed much of practical value, but space will not permit a detailed description. Then followed a period of rapid development. The use of oil as an insulating and cooling medium was adopted and core and copper losses were reduced. Other details such as improved construction, methods of dissipating heat, and increased efficiency and regulation have resulted in the construction of unusually large and high voltage units.

Basic Principles.—If a current be passed through a coil of wire encircling a bar of soft iron, the iron will become a magnet; when the current is discontinued the bar loses its magnetization.

Conversely: If a bar of iron carrying a coil of wire be



FIGS. 2.288 to 2.292.—Elementary transformers illustrating basic principles. The working of a transformer is due to what is known as *mutual induction between two circuits when an intermittent or alternating current flows in one of the circuits.* The effect of mutual induction may be explained by the aid of fig. 2.288. Whenever circuit **A**, is closed by the switch allowing a current to pass in a given direction, a momentary current will be induced in circuit **B**, as indicated by the galvanometer. A similar result will follow on the opening of circuit **A**, the difference being that the momentary induced current occurring at closure moves in a direction opposite to that in the battery circuit, while the momentary current at opening moves in the same direction. Currents besides being induced in circuit **B**, at *make* or *break* of circuit **A**, are also induced when the current in circuit **A**, is fluctuating in intensity. This intermittent or alternating current is necessary for the operation of a transformer. With intermittent current most marked results are observed when the make or break is sudden. Since the current can be stopped quicker than it can be started, the induction is greatest at *break*, hence ignition apparatus is designed to produce a spark at break. In fig. 2,289 the inductive effect is very feeble and successively better results are obtained in figs. 2,290 to 2,292. In fig. 2,288, circuit **A**, in which a current is passed called the *primary circuit*, and circuit **B**, in which a current is induced, the *secondary circuit*. Similarly, in fig. 2,289 the coil of circuit **A**, is called the *primary winding*, and that of circuit **B**, the *secondary winding*.

magnetized in a direction at right angles to the plane of the coil a momentary electric pressure will be induced in the wire; if the magnetization be reversed (by reversing the current), another momentary pressure will be induced in the opposite direction in the coil.

These actions are fully explained in Chaps. 10 and 11, and as they are perfectly familiar phenomena, a detailed explanation of the principles upon which they depend is not necessary here.

From the first two statements given above it is evident that if a bar of iron be provided with two coils of wire, one of which is supplied from a

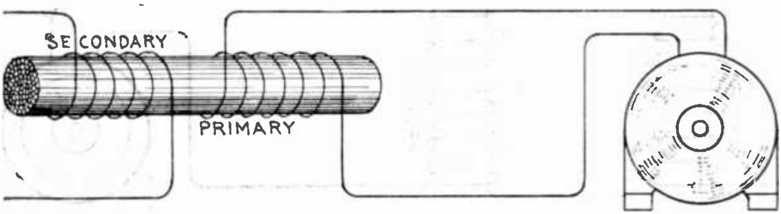


FIG. 2,293.—Diagram of elementary transformer with non-continuous core and connection with single phase alternator. The three essential parts are: primary winding, secondary winding, and an iron core.

source of alternating current, as shown diagrammatically by fig. 2,293, at each impulse of the exciting current a pressure will be induced in the secondary coil, the direction of these impulses alternating like that of the exciting current. *This is known as the transformer action.*

Ques. What name is given to the coil through which current from the source flows?

Ans. *The primary winding.*

Ques. What name is given to the coil in which voltage is induced?

Ans. *The secondary winding.*

Similarly, the current from the source (alternator) is called the *primary current* and the induced current, the *secondary current*.

Ques. What is the objection to the elementary transformer shown in fig. 2,293?

Ans. The non-continuous core. With this type core, the flux emanating from the north pole of the bar has to return to the south pole through the surrounding air; and as the re-

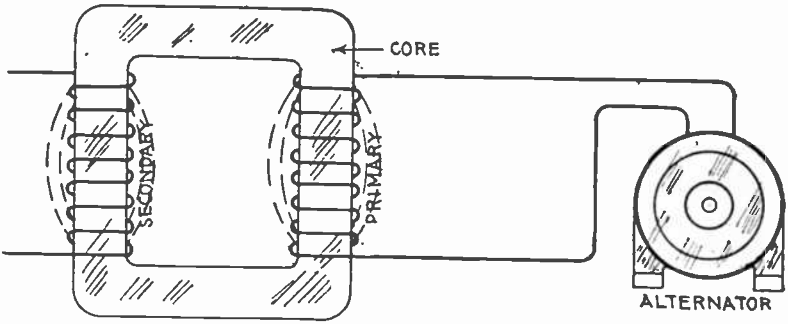


FIG. 2,294.—Diagram of elementary transformer with continuous core and connections with alternator. The dotted lines show the leakage of magnetic lines. To remedy this the arrangement shown in fig. 2,295 is used.

luctance of air is much greater than that of iron, the transformer will draw a very large exciting current. This is due to the fact that the flux in the transformer core remains approximately constant.

Ques. How is this overcome?

Ans. By the use of a continuous core as shown in fig. 2,294.

Ques. Is this the best arrangement, and why?

Ans. No. If the windings were put on as in fig. 2,294, the leakage of magnetic lines of force would be excessive, as indicated by the dotted lines. In such a case the lines which leak through air have no effect upon the secondary winding, and are therefore wasted.

Ques. How is the magnetic leakage reduced to a minimum in commercial transformers?

Ans. In these, and even in ordinary induction coils (the

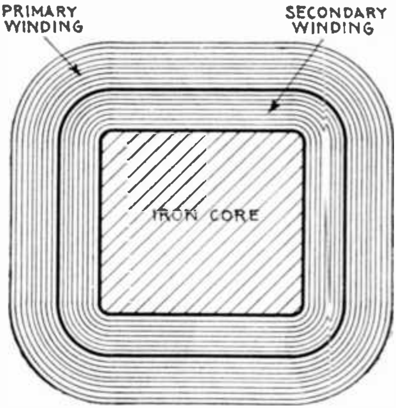
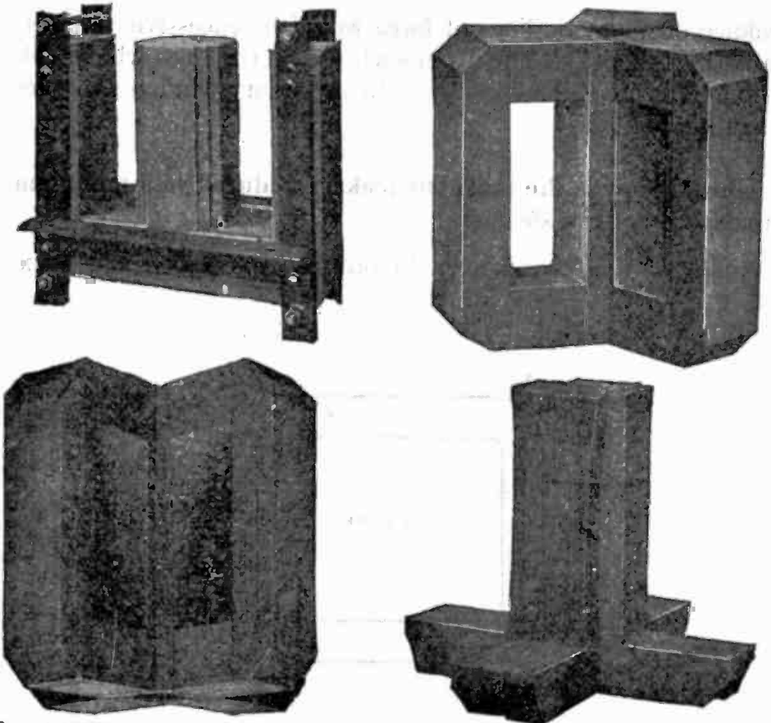


FIG. 2,295.—Cross section showing concentric arrangement of primary and secondary windings on core. One is superposed on the other. This arrangement compels practically all of the magnetic lines created by the primary winding to pass through the secondary winding.

operating principle of which is the same as that of transformers) the magnetic leakage is reduced to the lowest possible amount by arranging the coils one within the other, as shown in cross section in fig. 2,295, or by interleaving.

The Induced Voltage.—The property of a transformer that makes it of great value for most purposes is that *the voltage of the induced currents may be increased or diminished to any*



FIGS. 2,296 to 2,299.—General Electric core construction. Fig. 2,296, two part distributed core partially assembled; fig. 2,297, three part distributed core; fig. 2,298, four part distributed core; fig, 2.299, four part distributed core partly assembled. *The two part* distributed cores are assembled from straight laminations so that the center leg is of cruciform section and the two outer legs of rectangular section. The end laminations are inserted after the windings have been assembled. These cores are strongly clamped by means of structural steel parts which are also utilized in securing the core and coils in the tank. ***The three and four part*** cores are built up using L shaped laminations assembled in such a manner as to secure a comparatively large center section with magnetic circuits radiating at 120 degrees or 90 degrees, respectively. These laminations are interlocked in the center section. The use of L shaped punchings materially improves the designs by reducing the number of joints in the magnetic circuit to two, and thus materially lowering the exciting current. The three part core is so assembled that a nine sided center leg is produced which gives practically a circular form on which the coils are wound. In the four part core, a center leg having four sides with well rounded corners is secured so that the winding makes no sharp bends, and is either circular or nearly circular in form depending on the details of design of the core. The outer laminations closing the magnetic circuits are assembled after the winding operation is completed. The three part core is clamped by means of metal plates being held together by a bolt passing through the center of the core. In the four part core metal straps around the outer legs serve to hold these clamping plates together. These clamping plates in addition serve as a means of clamping the core and coils in the tank.

extent depending on the relation between the number of turns in the primary and secondary winding.

Rule.—*The voltage of the secondary current is (approximately)* to the voltage of the primary current as the number of turns of the secondary winding is to the number of turns of the primary winding.

Example.—If ten amperes flow in the primary winding and the transformation ratio be 10, then $10\times10=100$ amperes will flow through the secondary winding.

Thus, a direct proportion exists between the pressures and turns in the two windings and an inverse proportion between the amperes and turns, that is:

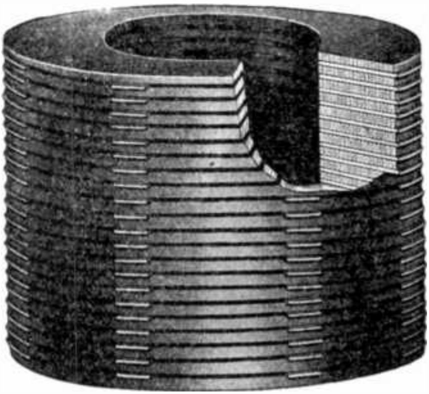


FIG. 2,300.—Moloney disc type coils showing arrangement of wires and spacing strips in column of coils. ***Disc type coils*** are used in large high voltage transformers. These coils are wound with double cotton covered ribbon wire; only one turn per layer to keep down stresses between layers. The layers are separated by several pieces of heavy insulating paper. This separation is greatly increased for approximately 10% of the turns near the line leads. Additional insulation is also provided by wrapping the conductor with varnished cambric.

FIG. 2,301.—Moloney open or drum type winding. ***This form of winding*** is used for the lower voltages in the larger sizes of transformers. Square or flat strap copper is used in this type winding. The different layers of the wire are wound straight across the entire coil. Several conductors of small cross section are used in parallel, practically eliminating eddy current losses. Ample ducts are placed next to each layer of wire. Sometimes both high voltage and low voltage are wound in open drum type and then the high voltage to low voltage insulation is placed over the low and the high wound directly over this insulation.

primary voltage: secondary voltage = primary turns: secondary turns

primary current: secondary current = secondary turns: primary turns

From the above equations it is seen that the watts of the primary circuit equal the watts of the secondary circuit.

Ques. Are the above relations strictly true, and why?

Ans. No, they are only approximate, because of transformer losses.

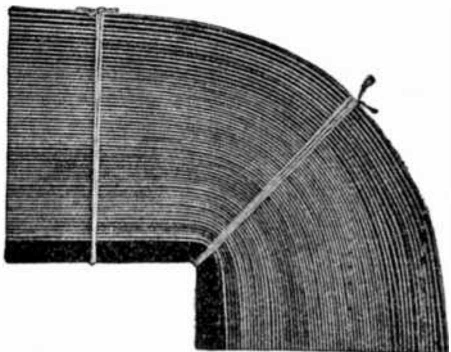


Fig. 2,302.—Close up detail of Wagner transformer coil.

In the above example, the total wattage in the primary circuit is $1{,}000 \times 10 = 10$ *kw.*, and that in the secondary circuit is $100 \times 100 = 10$ *kw.* Hence, while both volts and amperes are widely different in the two circuits, the watts for each are the same in the ideal case, that is, assuming perfect transformer action or 100% efficiency.

Now the usual loss in commercial transformers of this size is about 3% at full load, so that the actual watts delivered in the secondary circuit are: $(100 \times 100) \times 97\% = 9.7$ *kw.*

The No Load or Exciting Current.—When the secondary winding of a transformer is open or disconnected from the secondary circuit no current will flow in the winding, but a very small current called the *no load current* will flow in the primary circuit.

The reason for this is as follows: The alternating current flowing in the primary winding causes repeated reversals of magnetic flux through the

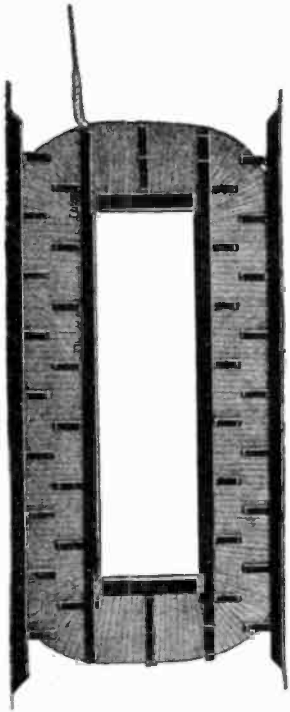


FIG. 2,303.—Wagner pancake type power transformer coil taped and treated.

FIG. 2,304.—Wagner pancake type coil assembly showing spacers and channels for oil circulation, and method of bracing the coils. It will be noted that projections from the insulating channels are staggered to obtain mechanical strength with freedom of oil circulation.

FIGS. 2,305 to 2,307.—Wagner transformer construction 1. Core type, iron and coil assembly. The two coils shown are for a 2,300 volt single phase, 60 cycle distribution transformer. Each of these coils consists of a high and low voltage winding. The low voltage coil is placed nearest to the core and the high voltage coil is wound over it. The insulation between the two coils is mica and varnished muslin.

iron core. These variations of flux induce pressures in both coils; that induced in the primary called the *reverse pressure* is opposite in direction and very nearly equal to the impressed pressure, that is, to the pressure applied to the primary winding. Accordingly the only force available to cause current to flow through the primary winding is the difference between the impressed pressure and reverse pressure, this difference being called the *effective pressure*.

The Magnetizing Current.—The magnetizing current of a transformer is sometimes spoken of as that current which the primary winding takes from the mains when working at normal pressure. The *true magnetizing current* is that component of this total no load current which is in quadrature with the supply pressure. The remaining component has to overcome the various iron losses, and is therefore in phase with the supply pressure. This component is very small if the transformer be well designed, and if it be worked at low flux density. The relation between these two components determines the power factor of the no load current.

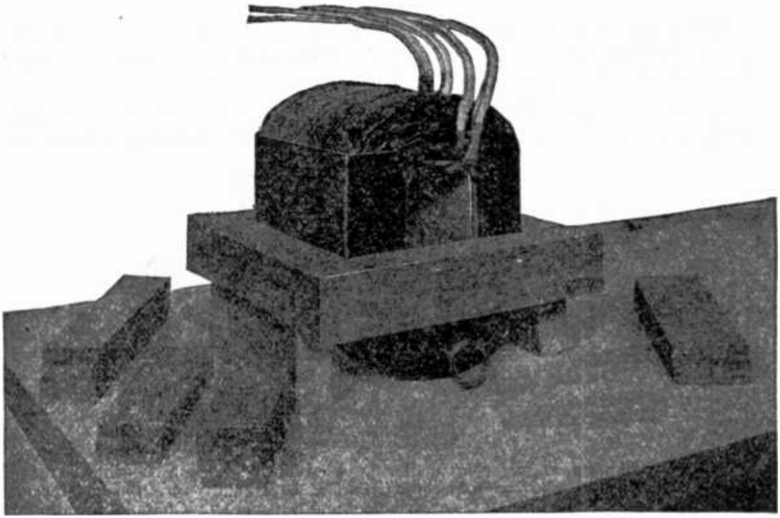


FIG. 2,308.—Wagner transformer construction 2. Shell type iron and core assembly of a 15 *kva.* distribution type transformer coil.

Action of Transformer with Load.—If the secondary winding of a transformer be connected to the secondary circuit by closing a switch so that current flows through the secondary winding, the transformer is said to be *loaded.*

The action of this secondary current is to oppose the magnetizing action of the slight current already flowing in the primary winding, thus decreasing the maximum value reached by the alternating magnetic flux in the core, thereby decreasing the induced pressure in each winding.

The amount of this decrease, however, is *very small*, inasmuch as a very small decrease of the induced pressure in the primary coil greatly increases the difference between the pressure applied to the primary coil and the opposing pressure induced in the primary coil, so that the primary current is greatly increased. In fact, *the increase of primary current due to the loading of the transformer is just great enough* (*or very nearly*) *to exactly balance the magnetizing action of the current in the secondary coil;* that is, the flux in the core must be maintained approximately constant by the primary current whatever value the secondary current may have.

When the load on a transformer is increased, the primary of the transformer automatically takes additional current and power from the supply mains in direct proportion to the load on the secondary.

When the load on the secondary is reduced, for example by turning off lamps, the power taken from the supply mains by the primary coil is auto-

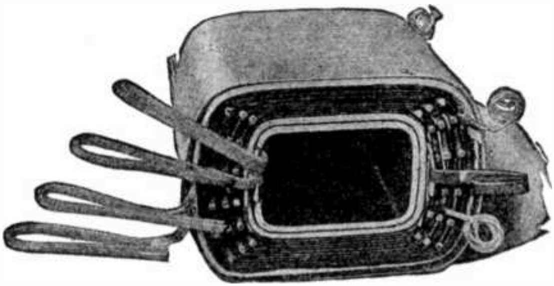


FIG. 2,309.—Wagner transformer construction 3. View of 15 *kva.* coil showing oil ducts. ***Shell type coils*** are started upon insulation that lies between the core iron and the low voltage winding. First one half of the low voltage winding is put on. On top of this winding and well insulated from it by mica and varnished muslin is placed the high voltage winding. The high voltage winding has spacers in it which hold the individual layers of wire apart and allow room for oil circulation. Over this high voltage winding is placed the other half of the low voltage winding. The entire coil is taped.

matically reduced in proportion to the decrease in the load. This automatic action of the transformer is due to the balanced magnetizing action of the primary and secondary currents.

Classification of Transformers.—As in the case of motors, the great variety of transformer makes it necessary that a classification, to be comprehensive, must be made from several points of view, as:

1. With respect to the transformation, as

a. Step up transformers;
b. Step down transformers.

2. With respect to the arrangement of the coils and magnetic circuit, as

a. Core transformers;
b. Shell transformers;
c. Distributed core, sometimes called modified shell type.

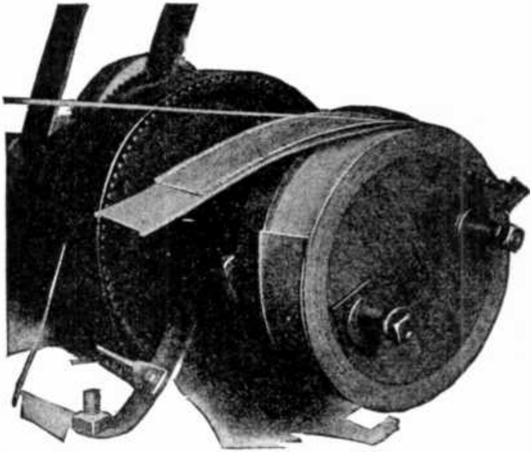


FIG. 2,310.—Wagner transformer construction 4. Circular type coil for high voltage units. Method of applying crimped paper insulation. After a layer of wire has been placed on the coil two strips of crimped insulation back to back are placed on the coil and the winding operations continued to bind the insulation to the coil.

3. With respect to the kind of circuit they are to be used on, as

a. Single phase transformers;
b. Polyphase transformers.

4. With respect to the method employed in cooling, as

a. Air cooled { natural draught / forced draught }

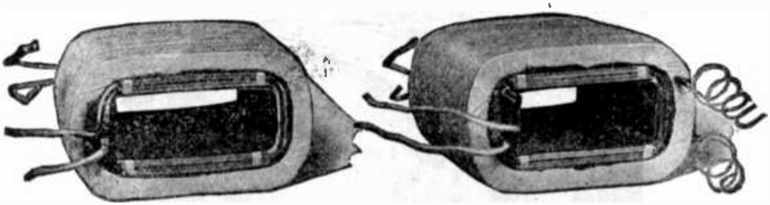
b, Self cooled }
c. Forced oil cooled } oil immersed
d. Water cooled }

5. With respect to the nature of their output, as

a. Constant pressure transformers;
b. Constant current transformers;
c. Current transformers;
d. Auto-transformers.

6. With respect to the kind of service, as

a. Distribution;
b. Power.



FIGS. 2,311 and 2,312.—Wagner transformer construction 5. Core type construction, 7½ *kva.* coil taped and ready for assembling core. *Distribution transformer coils* are wound either directly upon the core or upon forms. In the latter case the forms are removable and the cores are assembled in the coils after the winding operation is completed. The winding of coils directly upon the core produces an extremely heavy pressure in the core with an accompanying increase in eddy current losses, and also results in a winding which is more difficult to repair than when the coils are wound on a form. The coils of core type transformers have the low voltage winding on the inside next to the core and the high voltage winding on the outside, as far as possible from the core.

7. With respect to the circuit connection that the transformer is constructed for, as

a. Series transformers;
b. Shunt transformers.

8. With respect to location.

a. Indoor;
b. Outdoor.

Step Up Transformers.—This form of transformer is used to transform a low voltage current into a high voltage current. Such transformers are employed at the generating end of a transmission line to raise the voltage of the alternators to such value as will enable the electric power to be economically transmitted to a distant point.

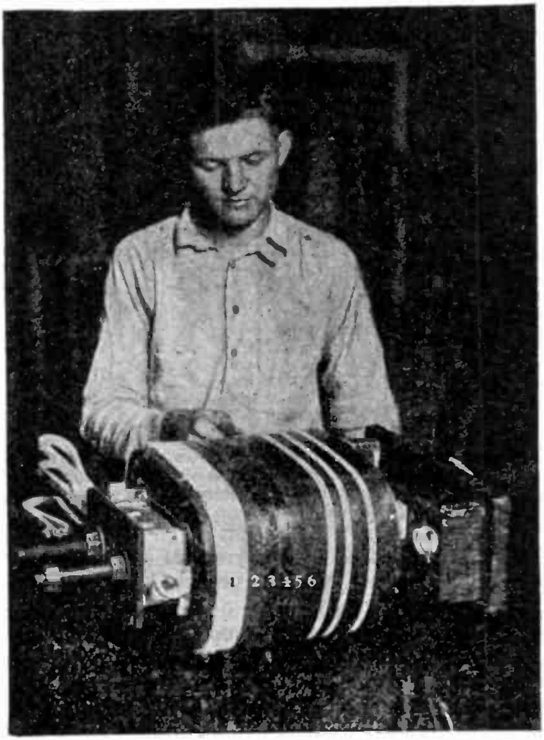


FIG. 2,313.—Wagner transformer construction 6. Coil and insulation details. 1, double cotton covered wire; 2, varnished muslin; 3, sheet mica; 4, sheet mica; 5, varnished muslin; 6, Fuller board.

Copper Economy with Step Up Transformers.—To comprehend fully the importance of the matter, it must be remembered that the energy supplied per second is the product of two factors, the current and the pressure at which that current is supplied; the magnitudes of the two factors may vary, but the value of the power supplied depends only on the product of the two.

For example, the energy furnished per second by a current of 10 amperes supplied at a pressure of 2,000 volts is exactly the same in amount

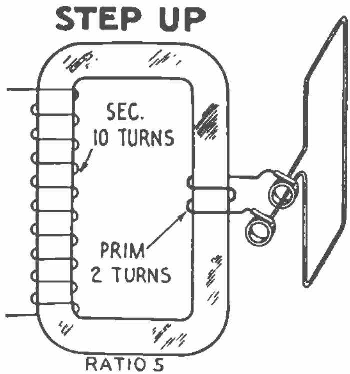


FIG. 2,314.—Diagram of elementary *step up* transformer. As shown the primary winding has two turns and secondary 10 turns, giving a ratio of voltage transformation of $10 \div 2 = 5$. Since only ⅕ as much current flows in the secondary winding as in the primary, the latter requires heavier wire than the former.

as that furnished per second by a current of 400 amperes supplied at a pressure of 50 volts; in each case, the product is 20,000 watts.

Now the loss of energy that occurs in transmission through a well insulated wire depends also on two factors, the current and the resistance of the wire, and in a given wire is proportional to the square of the current. In the above example the current of 400 amperes, if transmitted through the same wire as the 10 amperes current, would, because it is forty times as great, waste sixteen hundred times as much energy in heating the wire. It follows that, for the same loss of energy, the 10 ampere current at 2,000 volts may be carried by a wire having only $\frac{1}{1,600}$th of the sectional area of the wire used for the 400 ampere current at 50 volts.

The cost of copper conductors for the distributing lines is therefore very greatly economized by employing high pressures for distribution of small currents.

Step Down Transformers.—When current is supplied to consumers for lighting purposes, and for the operation of motors, etc., considerations of safety as well as those of suitability, require the delivery of the current at comparatively low pressures ranging from 100 to 250 volts for lamps, and from 100 to 600 volts for motors.

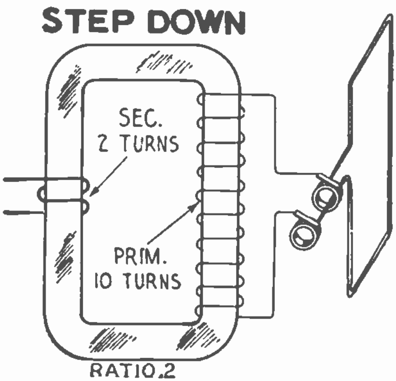


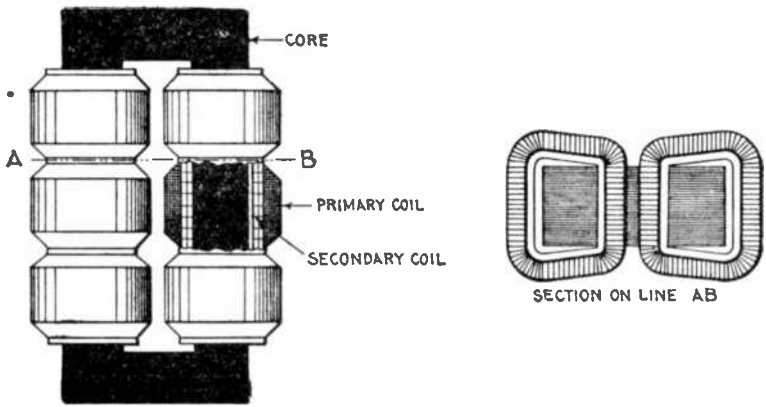
FIG. 2,315.—Diagram of elementary step down transformer. As shown the primary winding has 10 turns and the secondary 2, giving a ratio of voltage transformation of $2 \div 10 = .2$. The current in the secondary being 5 times greater than in the primary will require a proportionately heavier wire.

This means that the high pressure current in the transmission lines must be transformed to low pressure current at the receiving or distributing points by *step down transformers*, an elementary transformer being shown in fig. 2,315.

Transformers of this type have a large number of turns in the primary winding and a small number in the secondary, in ratio depending on the amount of pressure reduction required.

Core Transformers.—This type of transformer may be defined as one having an iron core, upon which the wire is wound in such a manner that the iron is enveloped within the coils, the outer surface of the coils being exposed to the air as shown in figs. 2,316 and 2,317.

Shell Transformers.—In the shell type transformer, as shown in fig. 2,318, the core is in the form of a shell, being built around and through the coils. A shell transformer has, as a



FIGS. 2,316 and 2,317.—Core type transformer with concentric winding. *It consists of* a central core of laminated iron, around which the coils are wound. A usual form of core type transformer consists of a rectangular core, around the two long limbs of which the primary and secondary coils are wound, the low tension coil being placed next the core.

rule, fewer turns and a higher voltage per turn than the core type.

Ques. What is the comparison between core and shell transformers?

Ans. The relative advantages of the two types has been the subject of considerable discussion among manufacturers; some companies who formerly built only shell type transformers, now build core types, while with other builders the opposite practice obtains.

Ques. Upon what does the manufacturers' choice between the two types chiefly depend?

Ans. Upon manufacturing convenience rather than operating characteristics.

The major insulation in a core type transformer consists of several

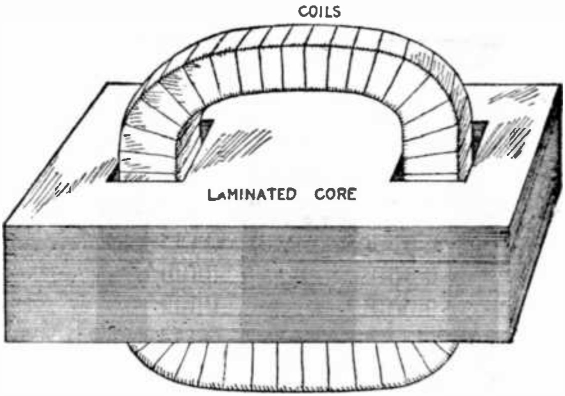


FIG. 2,318.—Shell type transformer. ***In construction,*** the laminated core is built around and through the coils as shown. For very heavy current ratings at low voltage this type has some advantages with respect to mechanical construction of windings, whereas in other ratings, particularly at high voltages, the core type is to be preferred, both in this respect and with respect to insulation.

large pieces of great mechanical strength, while in the shell type, there are required an extremely large number of relatively small pieces of insulating material, which necessitates careful workmanship to prevent defects in the finished transformer, when thin or fragile material is used.

Both core and shell transformers are built for all ratings; for small ratings the core type possesses certain advantages with reference to insulation, while for large ratings, the shell type possesses better cooling properties, and has less magnetic leakage than the core type.

Distributed Core Transformers.—An improved type of transformer has been introduced which can be considered either as two superposed shell transformers with coils in common, or as a single core type transformer with divided magnetic circuit and having coils on only one leg. It is best considered however, as a distributed core transformer, and for small sizes it possesses most of the advantages of both types. It can be constructed at less cost than can either a core or a shell transformer having the same operating characteristics and temperature limits.

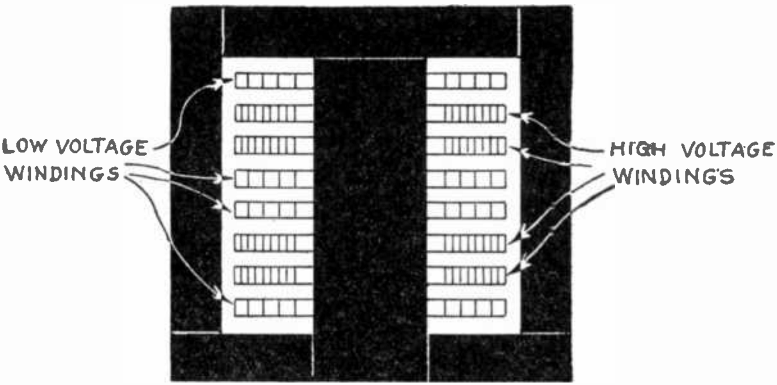


FIG. 2,319.—Plan of Core of General Electric distributed core transformer. The core used contains four magnetic circuits of equal reluctance, in multiple; each circuit consisting of a separate core. In this construction one leg of each circuit is built up of two different widths of punchings forming such a cross section that when the four circuits are assembled together they interlock to form a central leg, upon which the winding is placed. The four remaining legs consist of punchings of equal width. These occupy a position surrounding the coil at equal distances from the center, on the four sides; forming a channel between each leg and coil, thereby presenting large surfaces to the oil and allowing its free access to all parts of the winding. The punchings of each size transformer are all of the same length assembled alternately, and forming two lap joints equally distributed in the four corners of the core, thereby giving a magnetic circuit of low reluctance.

Ques. How is economy of construction obtained in designing distributed core transformers?

Ans. The cross section of iron in the central leg of the core is made somewhat less than that external to the coils, in order to reduce the amount of copper used in the coils.

Single and Polyphase Transformers.—A single phase transformer may be defined as *one having only one set of primary and*

FIG. 2,320.—General Electric core and coils of a core wound type H single phase, 60 cycle, 2,300 volt transformer, using four part distributed core. All single phase type H transformers, 50 *kva.* and smaller, below 6,000 volts, are core wound. In this range, by winding directly on the core, a fixed relation is established between turns, insulation and core, which insures maximum uniform insulation strength and efficiency. With this construction one half the low voltage winding is placed directly over the core insulation. The high voltage coils are then wound over the inner low voltage coils, with mica insulating pads between. The folded edges of the high voltage layer insulation locks the turns in place. Over the high voltage coils are placed other mica insulating pads and the second half of the low voltage winding is placed over this.

secondary terminals, and in which the fluxes in the one or more magnetic circuits are all in phase, as distinguished from a polyphase transformer, or combination in one unit of several single phase transformers with separate electric circuits but having certain magnetic circuits in common. In polyphase transformers there are two or more magnetic circuits through the core, and the fluxes in the various circuits are displaced in phase.

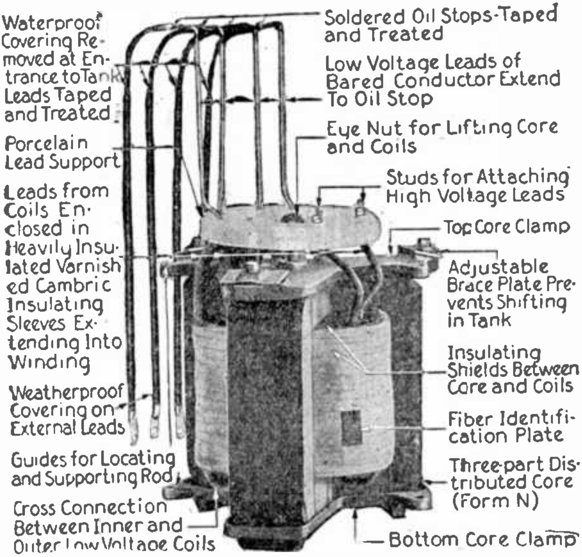


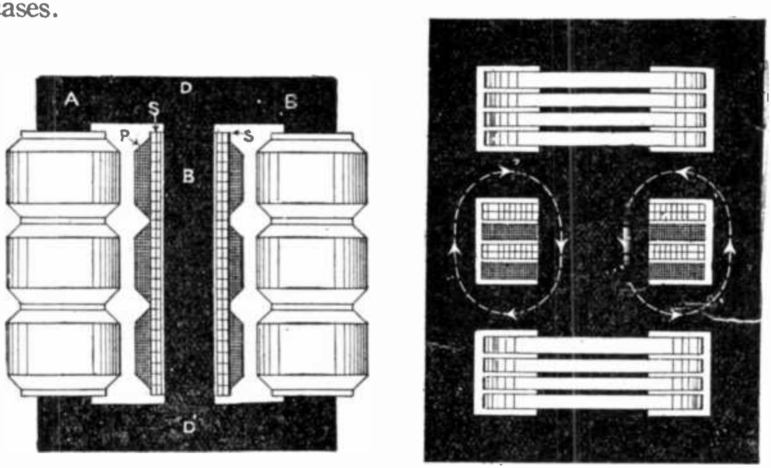
FIG. 2,321.—General Electric core and coils of a core wound type H single phase, 60 cycle, 2,300 volt transformer, using three part distributed core. The coils are provided with vertical oil ducts, which cross each conductor in the adjacent layers and assure uniform cooling. The number and location of these ducts vary with the size of the transformer.

Ques. Is it necessary to use a polyphase transformer to transform a polyphase current?

Ans. No, a separate single phase transformer may be used for each phase.

Ques. Is there any choice between a polyphase transformer and separate single phase transformers for transforming a polyphase current?

Ans. Each type of transformer may be preferable in specific cases.



FIGS. 2,322 and 2,323.—Core and shell types of three phase transformer. ***In the core type,*** fig. 2,322, there are three cores A, B, and C, joined by the yokes D and D'. This forms a three phase magnetic circuit, since the instantaneous sum of the fluxes is zero. Each core is wound with a primary coil P, and a secondary coil S. As shown, the primary winding of each phase is divided into two coils to ensure better insulation. The primaries and secondaries may be connected *star* or *mesh*. The core B, has a shorter return path than A and C, which causes the magnetizing current in that phase to be less than that in A and C phases. This has sometimes been obviated by placing the three cores so their corners form an equilateral triangle (as in fig. 2,297), but the extra trouble involved is not justified, as the unbalancing is a no load condition, and practically disappears when the transformer is loaded. ***The shell type,*** fig. 2,323, consists practically of three separate transformers in one unit. The flux paths are here separate, each pair of coils being threaded by its own flux, which does not, as in the core type, return through the other coils. This gives the shell type an advantage over the core type, for should one phase burn out, the other two may still be used, especially if the faulty coils be short circuited. The effect of such short circuiting is to prevent all but a very small flux threading the faulty coil.

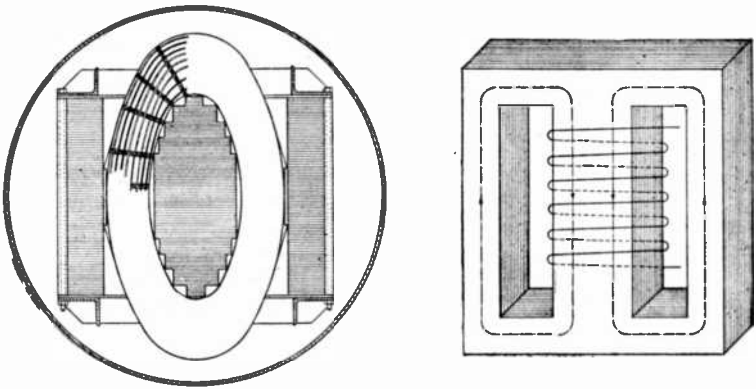
Ques. Name two varieties of polyphase transformer.

Ans. The core, and the shell types are shown in figs. 2,322 and 2,323.

Transformer Losses.—As previously mentioned, the ratio between the applied primary voltage and the secondary terminal voltage of a transformer is not always equal to the ratio of primary to secondary turns of wire around the core.

The commercial transformer is not a perfect converter of energy, that is, the **input,** or watts applied to the primary circuit is always more than the **output** or watts delivered from the secondary winding.

This is due to the various losses which take place, and the



FIGS. 2,324 and 2,325.—Sectional view of Pittsburgh single phase transformer, and magnet circuit.

difference between the input and output is equal to the sum of these losses which are:

1. The ***iron*** or ***core*** loss

Due to *a*, hysteresis; *b*, eddy currents; *c*, magnetic leakage (negligibly small).

2. The ***copper*** losses

Due to *a*, heating the conductors (the I^2R loss); *b*, eddy currents in conductors; *c*, stray losses (eddy currents in tank, clamps, etc.).

Hysteresis.—In the operation of a transformer the alternating current causes the core to undergo rapid reversals of

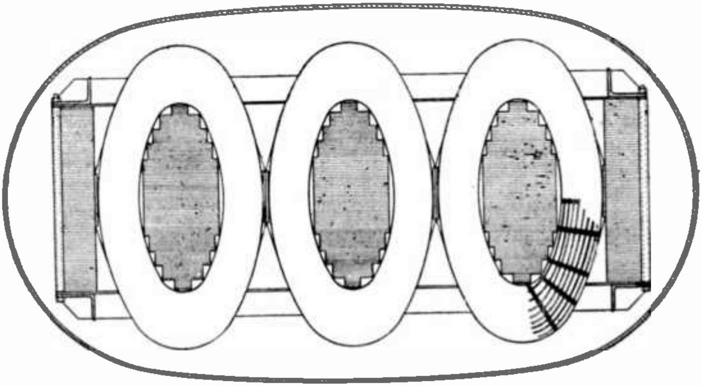


FIG. 2,326.—Cross section of Pittsburgh polyphase transformer.

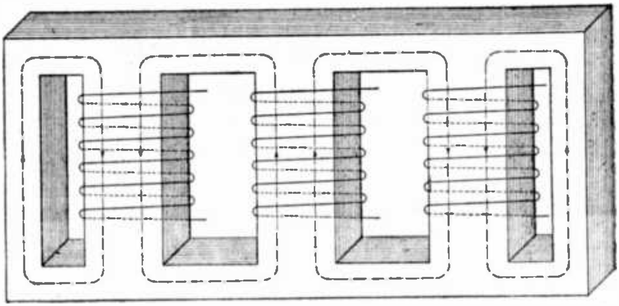


FIG. 2,327.—Diagram showing magnetic circuit of Pittsburgh polyphase transformer.

NOTE.—Silicon steel is used in the magnetic circuits of transformers. Core iron punchings are rolled to remove burrs and then carefully annealed. This process produces a scale of oxide on each punching which results in reduction of eddy current losses and produces transformers with consistently low iron losses.

NOTE.—*Cores.* It is a well known fact that the hysteresis loss in sheet steel is considerably less when the flux follows the natural grain of the steel produced by rolling than when it is required to travel at right angles to the grain. For this reason no T, U, or L shape punchings should be used. The pieces making up the cores should be so cut that the flux will follow the grain of the material. The cores should be assembled with the laminæ staggered, producing a lap joint of low magnetic reluctance.

magnetism. This requires an expenditure of energy which is converted into heat.

This loss of energy as before explained is due to the work required to change the position of the molecules of the iron, in

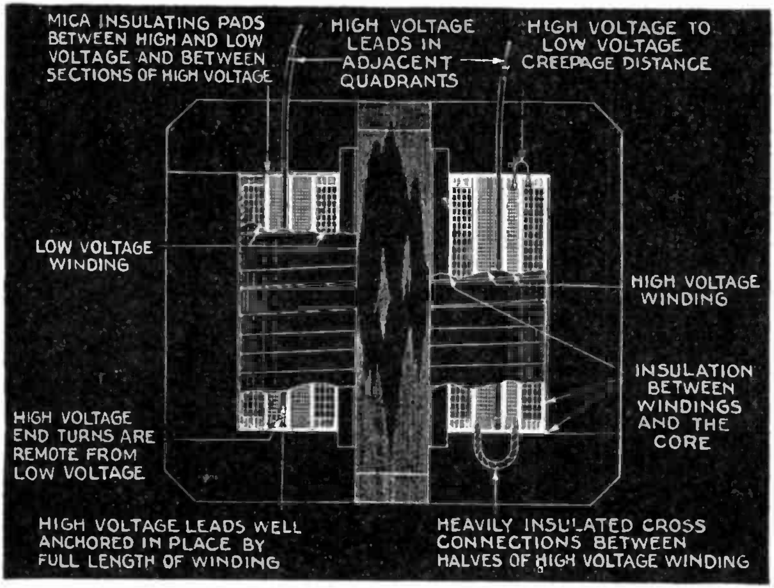


FIG. 2.328.—General Electric split coil construction for small distribution and power transformers. *The diagram shows* the improved method of winding high voltage coils. The incoming high voltage leads enter the winding between the two halves of the high voltage coils, and what would normally be the outside leads of the high voltage coils are connected together as a cross over, thus completing the circuit. The split coil construction provides the maximum distance between high voltage leads and the low voltage winding and also introduces the impedance of one half the high voltage winding between the low voltage winding and the voltage disturbance entering from the high voltage line. The object of this is to secure the maximum insulation strength between the high voltage and low voltage windings.

reversing the magnetization. Extra power then must be taken from the line to make up for this loss, thus reducing the efficiency of the transformer.

Ques. Upon what does the hysteresis loss depend?

Ans. Upon the quality and amount of the iron in the core, the magnetic density at which it is worked and the frequency.

Ques. With a given quality of iron how does the hysteresis loss vary?

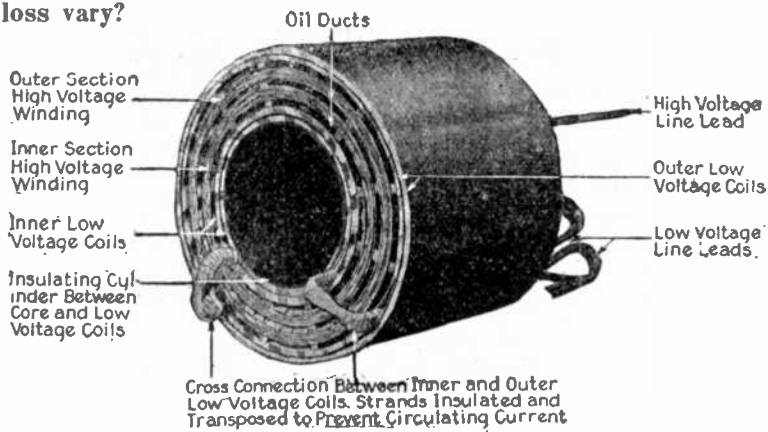


FIG. 2,329.—General Electric form wound coils for small low voltage, type H, form KS transformer showing arrangement of coils and insulation, added insulation between windings, and the ducts which provide channels for the circulation of oil. For transformers below 6,000 volts, sizes 75 to 500 *kva.*, the high and low voltage windings are arranged in the same way as for the core wound units, except that they are wound on a cylinder of Herkolite insulation, and are afterwards assembled on the core. A mica insulating pad is placed between the windings, and layer insulation with edges folded back and forth, to provide what is in effect a retaining wall, which securely locks all outside turns in position. The mechanical strength of the Herkolite cylinder on which the coils are wound assures the permanency of the coil structure.

Ans. It varies as the 1.6 power of the voltage with constant frequency.

Ques. In construction, what is done to obtain minimum hysteresis loss?

Ans. Specially annealed silicon steel is used for the core, and a low degree of magnetization is employed.

Eddy Currents.—The iron core of a transformer acts as a closed conductor in which small pressures of different values are induced in different parts by the alternating field, giving

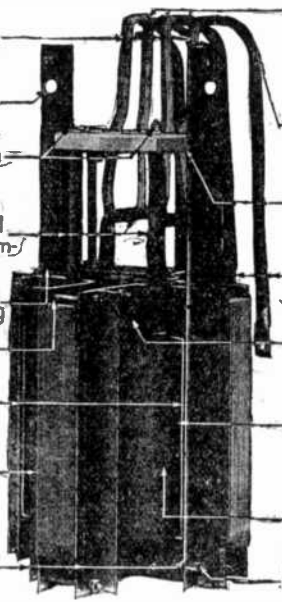


FIG. 2,330.—General Electric core and coils of a form wound type H form KS distribution transformer. For transformers 150 to 500 *kva*. in the 6,006, 11,000 and 13,200 volt classes, the interleaved disc type of winding is used. *In this construction* both high and low voltage coils are wound as flat discs with rectangular wire of one turn per layer and assembled with the high voltage and low voltage coils in alternate groups. Oil ducts are maintained between coils of the same group, and also between high voltage and low voltage groups. In the latter case, pressboard insulating collars are added. The ducts are maintained by self locking spacers in accurate columns so that every coil is rigidly supported at frequent intervals directly by the end clamps. The stack is assembled over a Herkolite cylinder, which forms a solid foundation for the winding as well as an insulating barrier between the coils and the center leg of the core.

rise to eddy currents. Energy is thus consumed by these currents which is wasted in heating the iron, thus reducing the efficiency of the transformer.

Ques. How is this loss reduced to a minimum?

Ans. By the usual method of laminating the core.

The iron core is built up of very thin sheet iron or steel stampings, and these are insulated from each other by varnish and are laid face to face at right angles to the path that the eddy currents tend to follow, so that the currents would have to pass from sheet to sheet, through the insulation.

Figs. 2,331 and 2,332.—General Electric disassembly of a form wound, type H, form KR distribution transformer. *In moderate voltages*, covered by the 6,600, 11,000 and 13,200 volt classes in sizes 100 *kva*. and below, the low voltage winding is wound on a Herkolite cylinder. Over the low voltage winding is assembled the high voltage coil group, consisting of backturn sections wound on an insulating and supporting cylinder of Herkolite. Collars between coil sections have ample extension to prevent creepage. Folded layer insulation is used throughout, assuring the permanent location of the outside turns of all coil sections and the maintenance of the graded spacing between the high voltage coil sections.

Ques. In practice, upon what does the thickness of the laminæ or stampings depend?

Ans. Upon the frequency.

The laminæ vary in thickness from about .014 to .025 inch, according as the frequency is respectively high or low.

Ques. Does a transformer take any current when the secondary circuit is open?

Ans. Yes, a "no load" current passes through the primary.

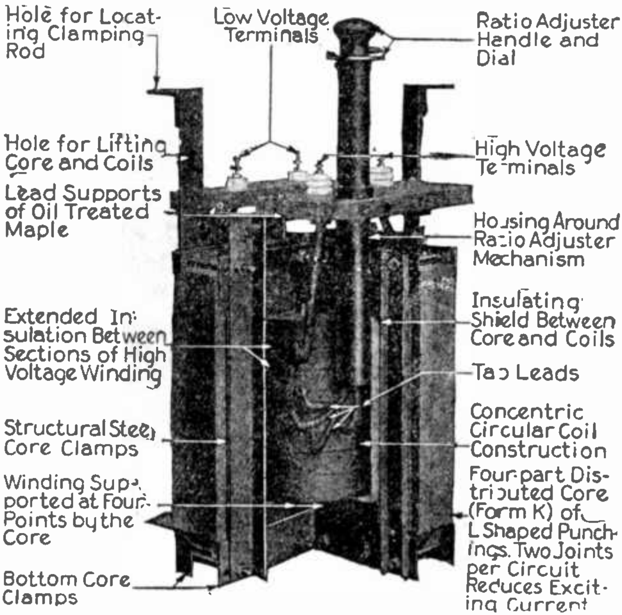
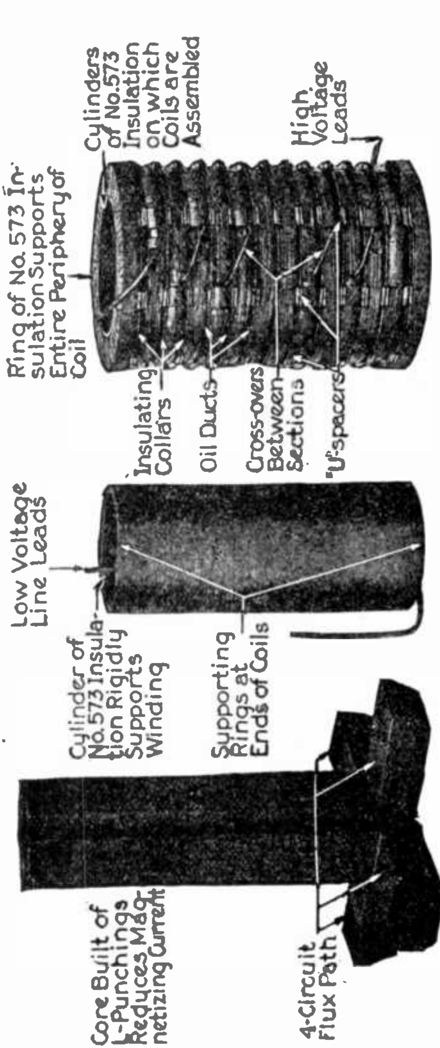


FIG. 2,333.—General Electric core and coils of a form wound, type H form KR distribution transformer.

Ques. Why?

Ans. The current thus supplied magnetizes the core and supplies energy to the core losses.

Ques. Are the iron or copper losses the more important, and why?



FIGS. 2,334 to 2,336.—General Electric core and windings of a form wound distribution transformer having cylindrical low voltage and disc high voltage coils.

Ans. The relative importance of iron and copper losses depends upon the type of service for which the transformer is designed.

The iron losses are going on as long as the primary pressure is maintained, and the copper losses take place only while energy is being delivered from the secondary.

NOTE.—*The core loss* of a transformer is *the energy required to magnetize and demagnetize the iron core due to the reversal of flux*. In distribution transformers this is very important and should be kept very low. The core loss varies in different sizes and different voltages. In the smaller and low voltage transformers the core loss never exceeds 1%; in the larger sizes it is as low as one half of 1%.

NOTE.—*The circular coil transformer* is built to withstand the mechanical forces of direct short circuit. The design is based upon the fact that the forces on a coil carrying a current tend to cause the coil to assume a circular form, with the result that there is no tendency for distortion due to radial forces in a coil already circular. In addition to this and other inherent advantages of the circular coil, the cores used should be designed to support the winding with minimum bracing against the forces tending to displace coils, which may be many tons.

Strictly speaking, on *no load* (that is when the secondary circuit is open) a slight copper loss takes place in the primary coil but because of its smallness is not mentioned. It is, to be exact, included in the expression "iron losses," as the precise meaning of this term signifies *not only the hysteresis and eddy current losses but the copper loss in the primary coil when the secondary is open.*

The importance of the iron losses is apparent in noting that in electric

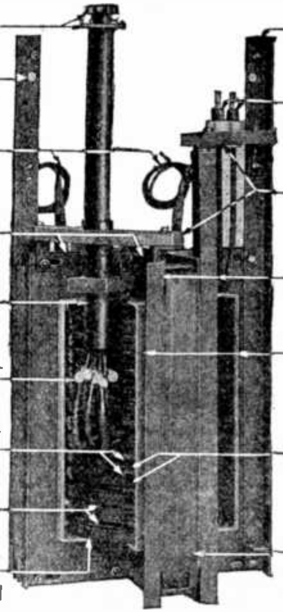


FIG. 2,337.—General Electric medium size 33,000 volt transformer with disc coil high voltage winding showing application of ratio adjuster.

lighting the lights are in use only a small fraction of the 24 hours, but the iron losses continue all the time, thus the greater part of each day energy must be supplied to each transformer by the power company to meet the losses, during which time no money is received from the customers.

Some companies make a minimum charge per month whether any current is used or not to offset the no load transformer losses and rent of meter.

Large power transformers are seldom connected to the supply circuit when they are not loaded and for this reason the copper losses are relatively more important.

Ques. How may the iron losses be reduced to a minimum?

Ans. By having short magnetic paths of large area and

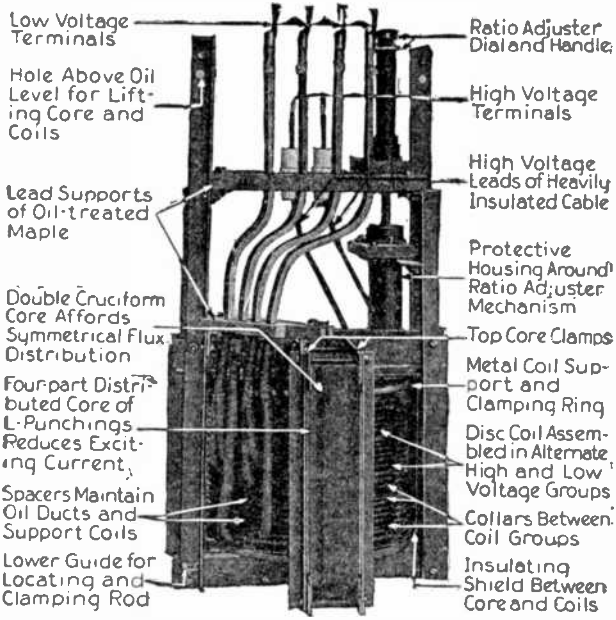


FIG. 2,338.—General Electric core and coils of a 2,300 volt type H, form KDD, interleaved disc coil distribution transformer.

using iron or steel of high permeability. The design and construction must keep the eddy currents as low as possible.

As before stated the iron losses take place continually, and since most transformers are loaded only a small fraction of a day it is very important that the iron losses should be reduced to a minimum.

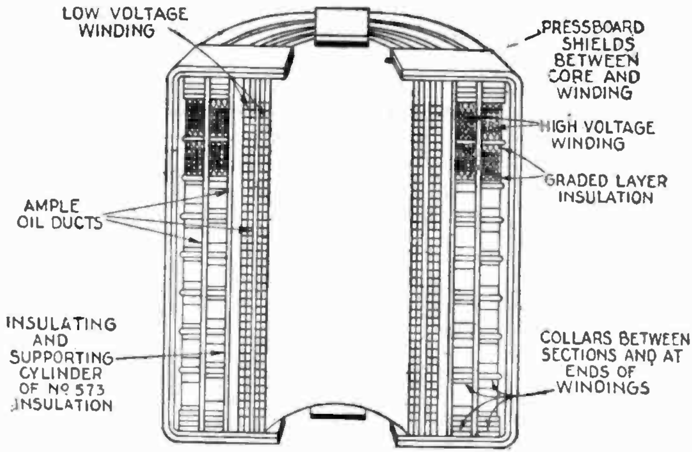
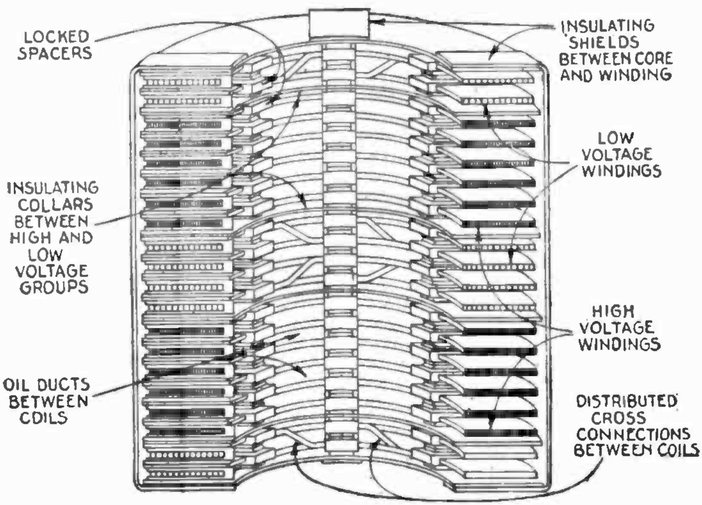


FIG. 2,339.—Details of coil construction of General Electric type H, form KR, transformer.



FIGS. 2,340.—Details of coil construction of General Electric type H, form KDD, transformer.

With a large number of transformers on a line, the magnetizing current that is wasted is considerable.

During May, 1910, the U. S. Bureau of Standards issued a circular showing that each watt saved in core losses was a saving of 88 cents, which is evident economy in the use of high grade transformers.

Copper Losses.—Since the primary and secondary windings of a transformer have resistance, some of the energy supplied will be lost by heating the copper. The amount of this loss is

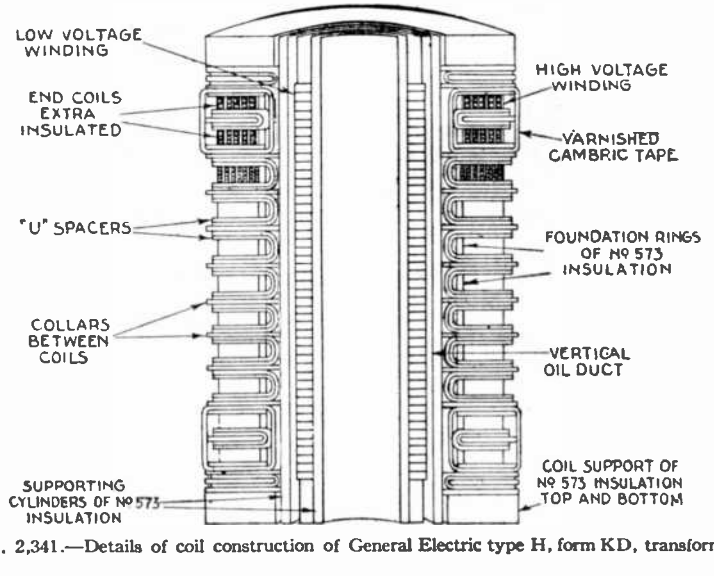
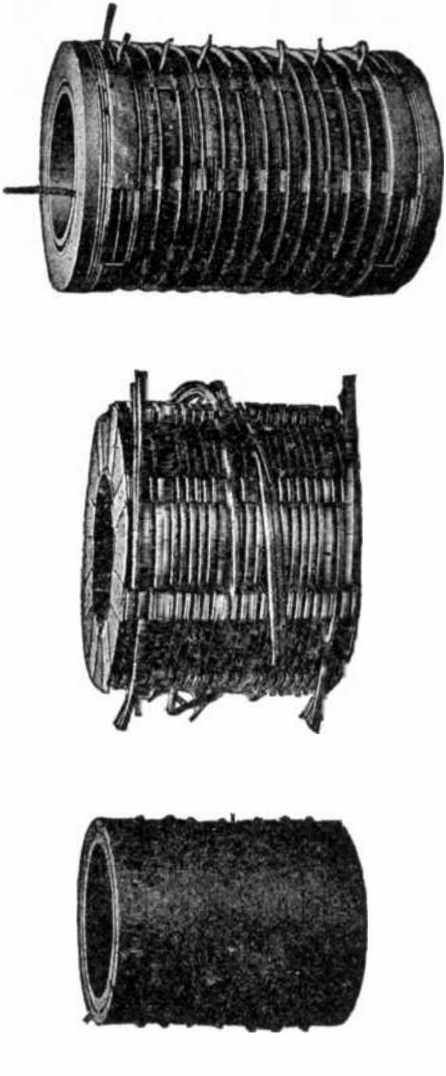


FIG. 2,341.—Details of coil construction of General Electric type H, form KD, transformer.

proportional to square of the current, and is usually spoken of as the I^2R loss.

Ques. Define the copper losses.

Ans. The copper losses are the sum of the I^2R losses of both the primary and secondary windings, the eddy current loss in



FIGS. 2,342 to 2,344.—External views showing appearance of General Electric transformer coils as shown in section, figs. 2,339 to 2,341

the conductors, and the stray losses due to eddy currents in the tank, clamps, etc.

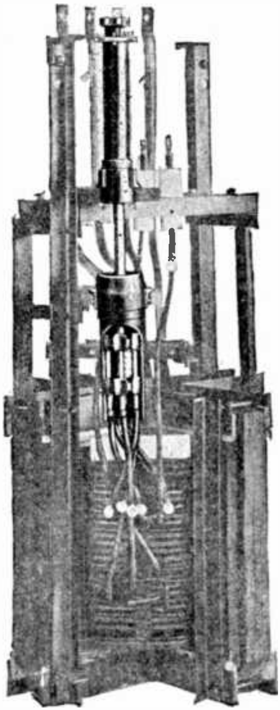
Ques. Are the eddy and stray current losses large?

Ans. In large transformers they are an appreciable per cent. of I^2R loss. In very small units they may be disregarded so that the sum of the I^2R losses of primary and secondary may be taken as the total copper loss for practical purposes.

Ques. What effect has the power factor on the copper losses?

NOTE.— *The regulation of a transformer is the drop in voltage from no-load to full-load.* This is usually specified in percentage of full load voltage and varies with the power factor of the load. The regulation in distributing transformers varies from approximately 2%.

Ans. Since the copper loss depends upon the current in the primary and secondary windings, it requires a larger current when the power factor is low than when high, hence the copper losses increase with a lowering of the power factor.



Ques. What effect other than heating has resistance in the windings?

Ans. It causes poor regulation.

This is objectionable, especially when incandescent lights are in use, because the voltage fluctuates inversely with load changes, that is, it drops as lamps are turned on and rises as they are turned off, producing disagreeable changes in the brilliancy of the lamps.

Cooling of Transformers.—Owing to the fact that a transformer is a stationary piece of apparatus, not receiving ventilation from moving parts, its efficient cooling becomes a very important feature of the design, especially in the case of large high pressure transformers.

FIG. 2,345.—General Electric ratio adjuster in position with Herkolite housing cut away to show mechanism. *This is a device* for conveniently changing taps in the high voltage winding. Its use eliminates the necessity of links or connectors on the connection board for making tap changes, or of bringing the tap leads any considerable distance from the coils. The ratio adjuster is actuated through an insulating rod connecting the mechanism with a dial and handle, which is located above the oil level and permits the changing of voltage ratio by means of a fractional turn of the handle. In the larger size transformers a hand hole in the cover is provided directly above the dial. When supplied with standard single phase transformers 150 to 500 *kva.* the handle is brought through the cover.

The effective cooling is rendered more difficult because transformers are invariably enclosed in more or less air tight cases, except in very dry situations, where a perforated metal covering may be permitted.

The final degree to which the temperature rises after continuous working for some hours, depends on the total losses in iron and copper, on the total radiating surface, and on the facilities afforded for cooling.

There are various methods of cooling transformers, the cooling mediums employed being

1. Air;
2. Oil;
3. Water.

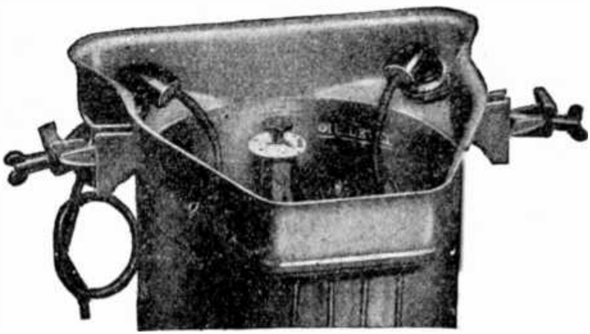


FIG. 2,346.—Interior view of General Electric 13,200 volt, form KR transformer, showing ratio adjuster dial and handle above oil level.

The means adopted for getting rid of the heat which is inevitably developed in a transformer by the waste energy is one of the important considerations with respect to its design.

Ques. What is the behavior of a transformer with respect to heating when operated continuously at full load?

Ans. The temperature gradually rises until at the end of some hours it becomes constant.

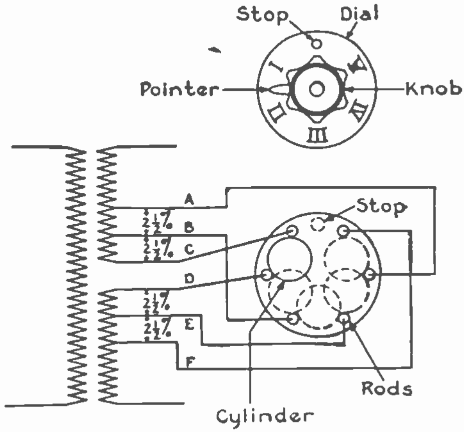
The difference between the constant temperature and that of the surrounding atmosphere is called the temperature rise at full load. *Its amount constitutes a most important feature in the commercial value of the transformer.*

Ques. Why is a high rise of temperature objectionable?

Ans. It causes rapid deterioration of the insulation, increased copper losses, and greater fire risk.

ADJUSTMENTS

Position	Connecting	Per Cent of Winding
I	C to D	100
II	B to D	97.5
III	B to E	95
IV	A to E	92.5
V	A to F	90



FIGS. 2,347 and 2,348.—Diagram of General Electric ratio adjuster connections to transformer with four 2½% taps. ***The adjustments are as shown to the left of the illustration.*** By a special design of the transformer winding and the use of a special mechanism involving ratio adjusters and oil circuit breakers, it is possible to provide for changes in connections while under load. Such a device would ordinarily be restricted to large transformers or transformer tanks, because of the cost. Load ratio control may be of special advantage in the case of tie in banks where it is necessary to make frequent adjustment in the transformers connecting two systems.

Air Cooled Transformers.—This name is given to all transformers which are cooled by currents of air without regard to the manner in which the air is circulated. There are two methods of circulating the air, as by

1. Natural draught;
2. Forced draught, or air blast.

Ques. Describe a natural draught air cooled transformer.

Ans. In this type, the case containing the windings is open at the top and bottom. The column of air in the case expands as its temperature rises, becoming lighter than the cold air on the outside and is consequently displaced by the latter, resulting in a circulation of air through the case. The process is identical with furnace draught.

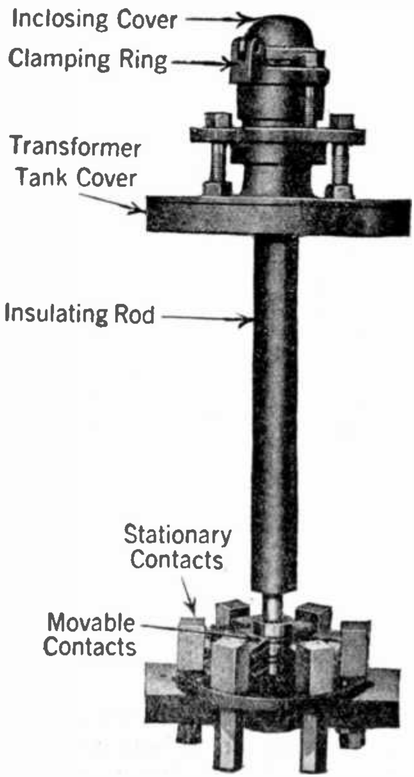


FIG. 2,349.—Wagner tap changer, including part external to the transformer case and the insulating rod and switch mechanism. This device makes it possible to change the taps quickly and conveniently during any kind of weather. *The design is such* that even with transformers equipped with an expansion tank the tap changing operation can be performed without removing oil from the tank and without loss of oil through the tap changers.

Ques. Describe a forced draught or air blast transformer.

Ans. The case is closed at the bottom and open at the top. A current of air is forced through from bottom to top as shown in fig. 2,350 by a fan.

Ques. How are the coils best adapted to air cooling?

Ans. They are built up high and thin, and assembled with spaces between them, for the circulation of the air.

Ques. What are the requirements with respect to the air supply in air blast transformers?

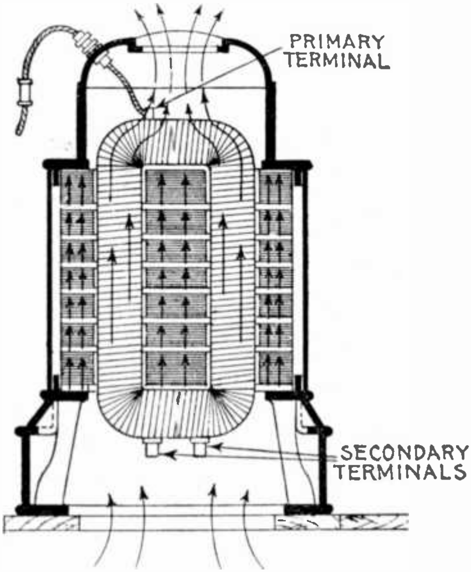


FIG. 2,350.—Forced draught or "air blast" transformer. As is indicated by the classification, this type of transformer is cooled by forcing a current of air through ducts, provided between the coils and between sectionalized portions of the core. The cold air is forced through the interior of the core containing the coils by a blower, the air passing vertically through the coils and out through the top. The amount of air going through the coils may be controlled independently by providing dampers in the passages.

Ans. Air blast transformers require a large volume of air at a comparatively low pressure. This varies from 1 to 1½ ozs. per sq. in. The larger transformers require greater pressure to over come the resistance of longer air ducts.

Ques. How much air is used ordinarily for cooling per kw. of load?

Ans. About 100 cu. ft. of air per minute per total kilowatt loss for maximum rated transformers, that is, transformers which are not designed to operate above their rated capacity.

Oil Cooled Transformers.—In this type of transformer the coils and core are immersed in oil and provided with ducts to

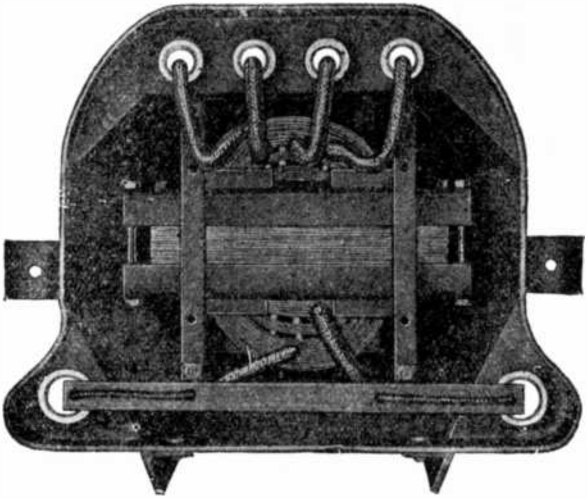


FIG. 2,351.—Pittsburgh single phase oil cooled distribution transformer showing assembly of core and coils in case.

allow the oil to circulate by convection and thus serve as a medium to transmit the heat to the case, from which it passes by radiation.

Ques. Explain in detail the circulation of the oil.

Ans. The oil, heated by contact with the exposed surfaces of the core and coils, rises to the surface, flows outward and descends along the sides of the transformer case, from the outer surface of which the heat is radiated into the air.

Ques. How may the efficiency of this method of cooling be increased?

Ans. By providing the case with corrugations or external tubes or radiators so as to increase the external cooling surface.

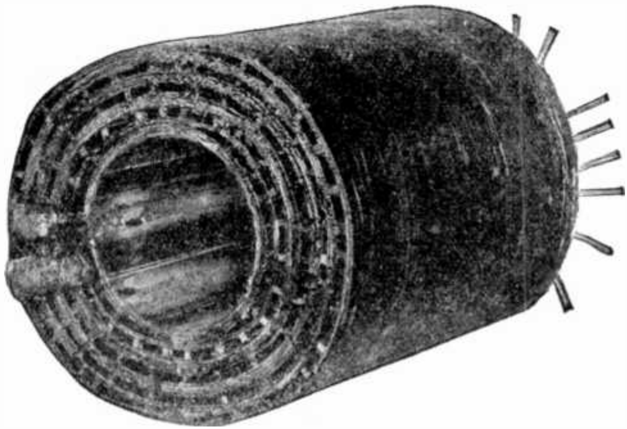


FIG. 2,352.—End view of Kulman transformer showing oil ducts. In the case of transformers wound for 2,300 volt, 4,600 volt and 6,900 volt primaries, the primary is placed between two sections of secondary. In transformers with primary voltages over 6,900, the secondary is wound on the core, then the primary is wound over the secondary with heavy insulation between. The voltage between the sections is kept at a minimum value, and the sections are separated a sufficient distance to allow the oil to completely surround them.

Ques. In what type of transformer is this mode of oil cooling used?

Ans. There is no limit to the size for which transformers of this type can be built. This is made possible in the large sizes by the use of external radiators.

NOTE.—Some manufacturers have abandoned the use of cast iron for tanks, using other material such as copper alloy steel, because cast iron is porous and will not hold hot transformer oil without leaking.

Ques. In what other capacities besides that of cooling agent, does the oil act?

Ans. It is a good insulator, preserves the insulation from oxidation, increasing the breakdown resistance of the insulation, and generally restores the insulation in case of puncture.

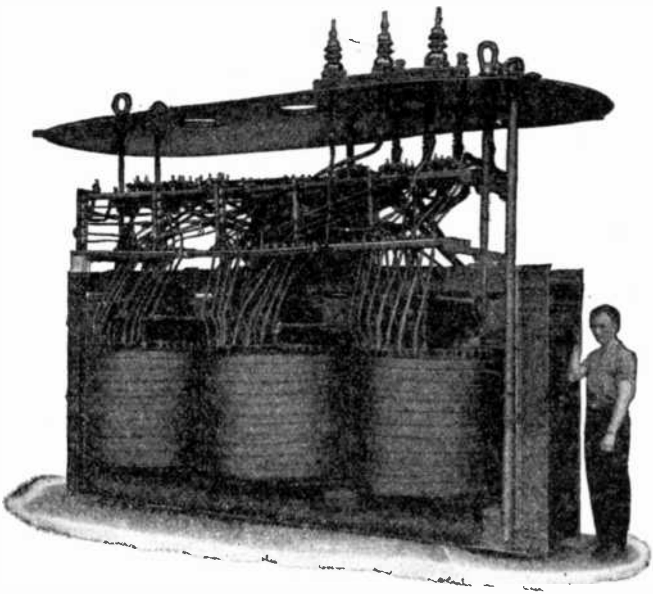


FIG. 2,353.—Core and coils of large 15,000 *kva.* Pittsburgh self-cooled by external radiator transformer on freight car ready for shipment.

Ques. What is an objection to oil?

Ans. The possibility of a central station fire being augmented by the presence of oil. Due to the high flash point of transformer oil, this affords but little extra hazard.

Ques. What kind of oil is used in transformers?

Ans. Mineral oil.

Ques. What are the requirements of a good grade of transformer oil?

Ans. It should have low viscosity, that is, it should flow freely at operating temperatures. It should not decompose or

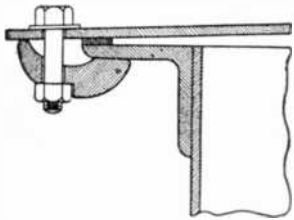


FIG. 2,354.—Pittsburgh method of clamping cover on transformer.

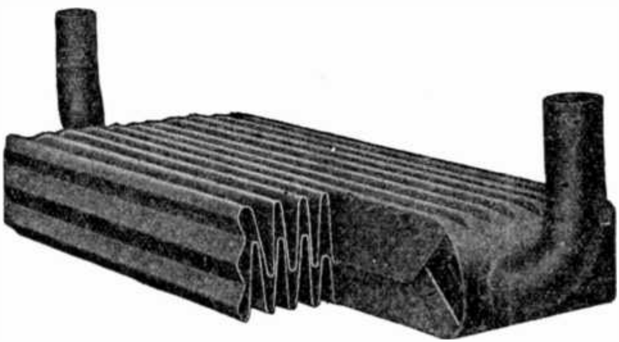


FIG. 2,355.—Pittsburgh Transformer Co. film radiator with section cut out, showing large radiating surface with very small film of oil.

throw down sludge under operating conditions. It must not contain moisture and should be free from acid, alkali or sulphur compounds.

Since the dielectric strength or insulating value of oil depends upon the water content, it may be determined by finding the break down voltage of a standard sample. This test may be quickly and accurately made by the use of a standard oil testing outfit.

A rough test consists of thrusting a red hot nail in the oil; if the oil "crackle," water is present. Moisture may be removed by raising the temperature slightly above the boiling point, 212° Fahr., but the time consumed (several days) is excessive.

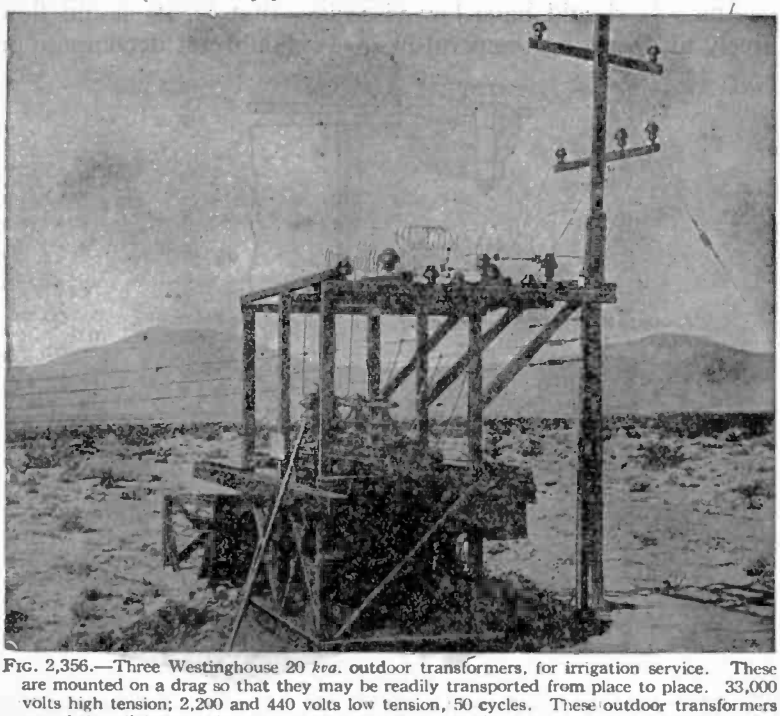


FIG. 2,356.—Three Westinghouse 20 *kva.* outdoor transformers, for irrigation service. These are mounted on a drag so that they may be readily transported from place to place. 33,000 volts high tension; 2,200 and 440 volts low tension, 50 cycles. These outdoor transformers are of the oil immersed, self-cooling type and have been developed to meet the requirements for transformers of capacities greater or of voltages higher than are usually found in distribution work. They are in reality distributing transformers for high voltage, outdoor installations, single or three phase service, for voltages up to 110,000. Where the magnitude of the load does not warrant an expensive installation, transformers of the outdoor type are particularly applicable. The cost of a building and outlet bushings which is often the item of greatest expense is eliminated where outdoor type transformers are installed.

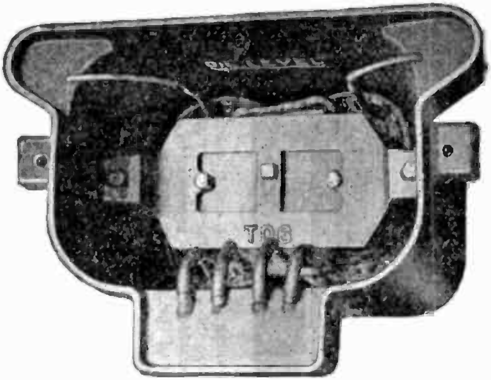


FIG. 2,357.—Duncan type B, 5 *kva*,2, 300 volt transformer viewed from the top, showing oil level marking and method of sealing in leads.

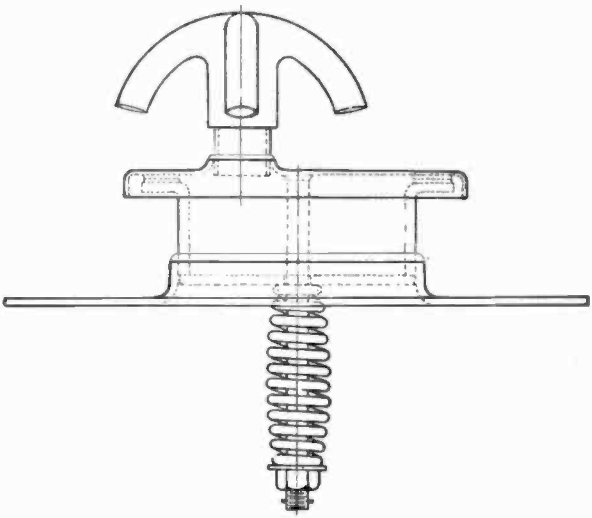
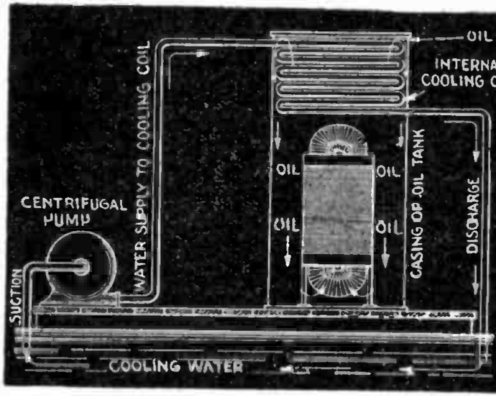


FIG. 2,358.—Pittsburgh automatic safety valve with Pittsburgh breather mounted. It has four outlets to the air and each outlet contains a copper gauze screen to prevent dust and dirt entering the transformer. These breathers allow for sufficient "breathing" in the transformer, at the same time preventing the entrance of moisture and dirt.



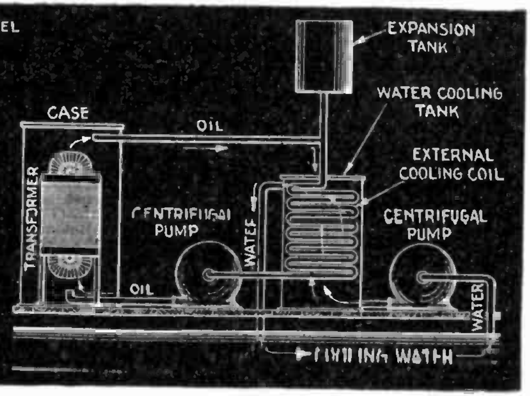


FIG. 2,359.—Water cooled transformer with internal cooling coil, that is, with cooling coil within the transformer case. In this type, the cooling coil, through which the circulating water passes, is placed in the top of the case or tank, the latter is filled with oil so that the coil is submerged. The oil acts simply as a medium to transfer the heat generated by the transformer to the water circulating through cooling coil. In operation a continual circulation of the oil takes place, as indicated by the arrows, due to the alternate heating and cooling it receives as it flows past the transformer coils and cooling coil respectively.

FIG. 2,360.—Water cooled transformer with external cooling coil. In this arrangement the cooling coil is placed in a separate tank as shown. Here forced circulation is employed for both the heat transfer medium (oil) and the cooling agent (water), two pumps being necessary. The cool oil enters the transformer case at the lowest point and absorbing heat from the transformer coils it passes off through the top connection leading to the cooling coil and expansion tank. Since the transformer tank is closed, an expansion tank is provided to allow for expansion of the oil due to heating. The water circulation is arranged as illustrated.

Forced Oil Cooled Transformers.—In this type of transformer the cooling of the core and windings is effected by forced circulation of the oil through the tank by means of piping and an external pump. The oil is cooled by being pumped through piping or radiators or through cooling coil immersed in running water. This method of cooling is usually used only when water cooled transformers are prohibited by lack of suitable water.

Water Cooled Transformers.—A water cooled transformer is one in which water is the cooling agent, and, in most cases, oil is the medium by which heat is transferred from the coils to

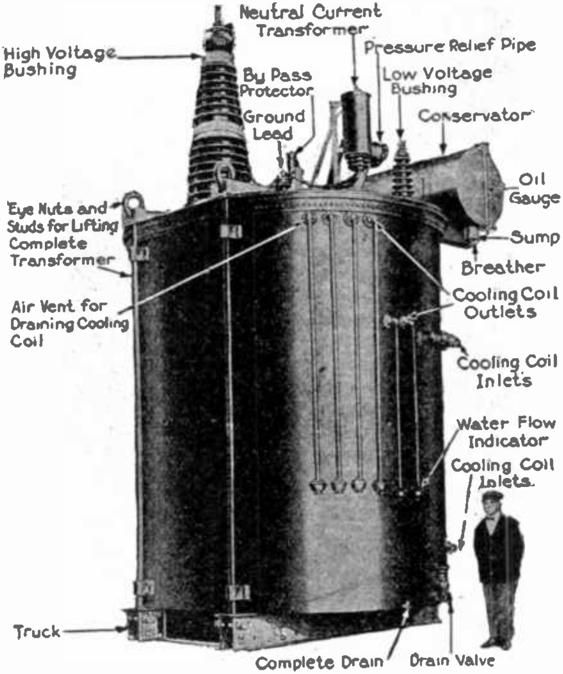


FIG. 2,361.—General Electric single phase water cooled outdoor transformer.

the water. In construction, pipes or a jacketed casing is provided through which the cooling water is passed by forced circulation, as shown in figs. 2,359 and 2,360.

In some special cases tubular conductors are provided for the circulation of the water.

Ques. How is a water cooled transformer cooled?

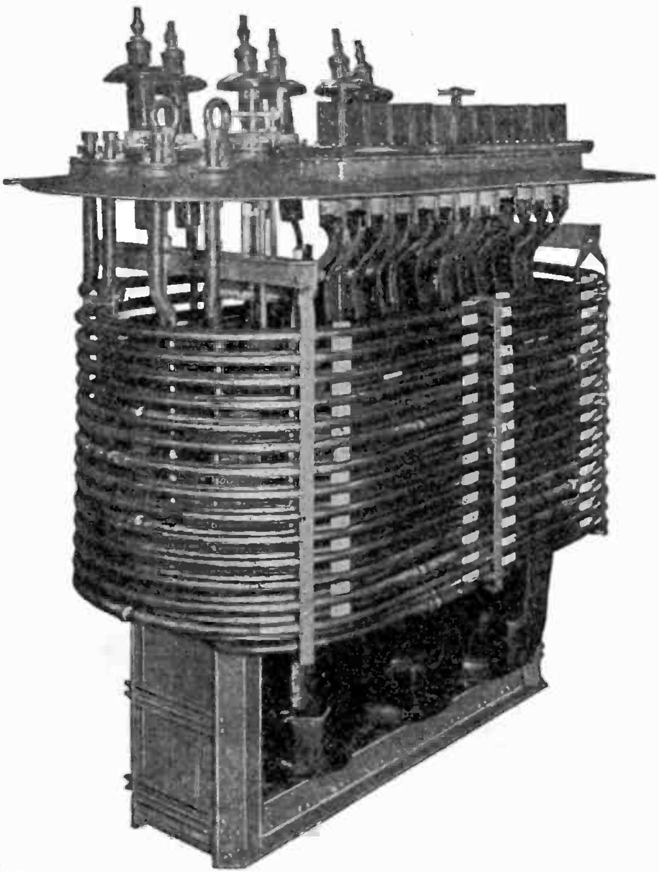


FIG. 2,362.—Pittsburgh water cooled power transformer showing core, coils and cooling pipes. Standard practice is to have the inlet and outlet of the cooling pipes pass through the arched cover through stufling boxes, with extra long glands to prevent moisture entering into the oil or leaking out of the tank. This construction permits the core and coils and the water cooling coil, together with the cover, to be removed by a crane in one operation for inspection and cleaning of the water cooling pipes.

Ans. Inside the transformer case near the top is placed a coil of wrought iron or copper pipe, through which the cooling water is pumped. The case is filled with oil, which by *thermo-circulation* flows upward through the coils, transferring the heat absorbed from the coils to the water; on cooling it becomes more dense (heavier) and descends along the inside surface of the casing.

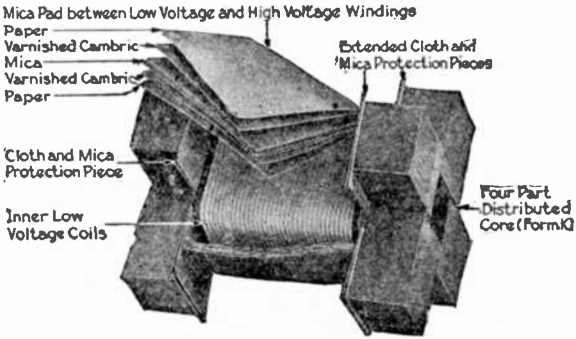


FIG. 2,363.—General Electric partially assembled type H transformer, showing mica insulation. It is necessary to have fireproof insulation in smaller sizes in order to insure protection of the low voltage circuit in case of burnout from abnormal operating condition.

Ques. How much circulating water is required?

Ans. It depends upon the difference between the initial and discharge temperature of the circulating water, and also upon the size of the transformer.

For a water temperature rise of 52° Fahr., 2.78 lbs. of water per minute is required per *kw.* of load.

Ques. In water cooled transformers how much cooling surface is required for the cooling coil?

Ans. The surface of the cooling coil should be from .3 to .5 sq. in. per watt of total transformer loss, depending upon the amount of heat which the external surface of the transformer case will dissipate.

Transformer Insulation.—This subject has not, until the last few years, been given the same special attention that many other electrical problems have received, although the development of the transformer from its original form, consisting of an iron core enclosed by coils of wire, to its present degree of refinement and economy of material, has been comparatively rapid.

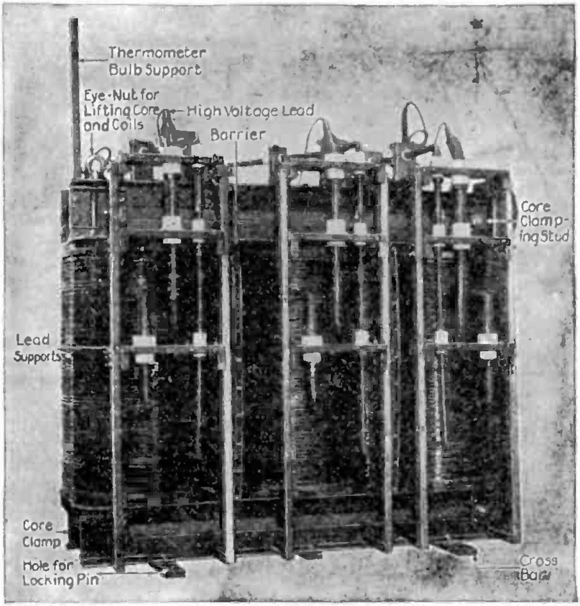


FIG. 2,364.—General Electric three phase 13,200 to 66,000 volt auto transformer. High voltage neutral solidly grounded. Interleaved disc windings.

In transformer construction it is obviously very important that the insulation be of the best quality to prevent burn outs and interruptions of service.

Ques. What is the "major" insulation?

Ans. The insulation placed between the windings and core and between the primary and secondary windings.

For large core type units with concentric windings, this insulation is simply and effectively secured by the use of special insulating cylinders and oil ducts extending the full length of the core. In the interleaved construction the major insulation between windings usually consists of sheets of pressboard and oil ducts, while between windings and core the above mentioned cylinders or pressboard sheets may be used.

For very small units the major insulation consists usually of mica sometimes applied as sheets, etc.

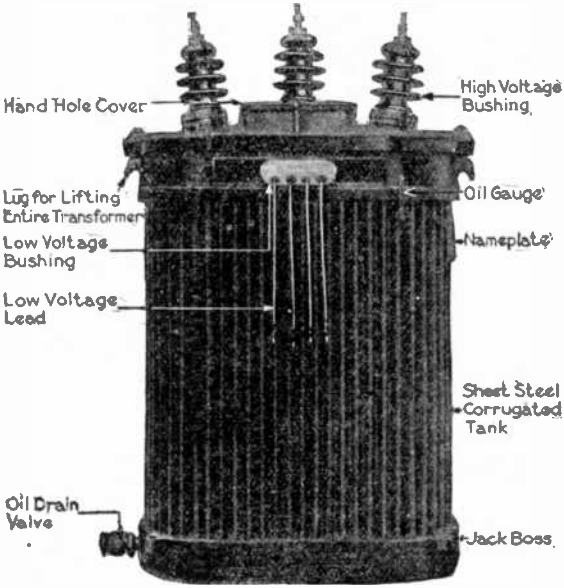


FIG. 2,365.—General Electric small power high voltage three phase transformer in corrugated tank. Three phase tanks are identical in construction with corresponding type single phase tanks, except for the difference in shape necessary to accommodate differently shaped cores and coils. The smaller three phase transformers are provided with smooth cast iron tanks, while the moderate and large sizes have tanks with corrugated sheet steel sides cast welded into cast iron bases and top rims.

Ques. Describe the "minor" insulation.

Ans. It is the insulation placed between adjacent turns and between coils of the same winding.

The minor insulation between coils of the same winding usually consists of pressboard sheets and oil ducts. For very small units treated cloth or fibre may be used. Since the difference of pressure is small between the adjacent turns, the insulation need not be very thick. It may consist of one or more wrappings of cotton or treated paper tape around each conductor. For small round conductors, enamel together with the cotton may be used.

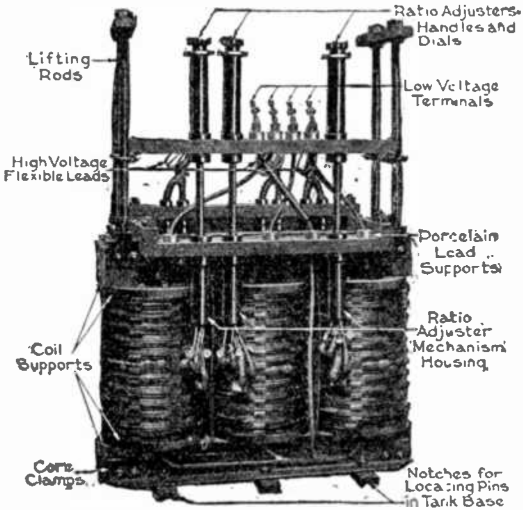


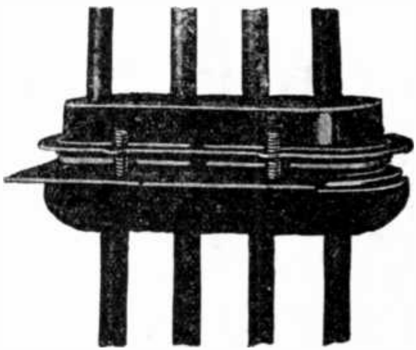
FIG. 2,366.—General Electric core and coils of small power high voltage, three phase transformer. The windings of three phase distribution and small power transformers are form wound in all sizes, with one phase assembled on each leg of the core. In arrangement, spacing and insulation the same general practice is followed as in the single phase designs.

Ques. What is the most efficient insulating material for transformers?

Ans. Mica.

It has a high dielectric strength, is fireproof, and is the most desirable insulator where there are no sharp corners. Its use, however, is limited to small units, where it can be easily applied.

Oil Insulated Transformers.—High voltage transformers are insulated with oil, as it is very important to maintain careful insulation not only between the coils, but also between the coils and the core. In the case of high voltage transformers, any accidental static discharge, such as that due to lighting, which might destroy one of the air insulated type, might be successfully withstood by one insulated with oil, for if the oil insulation be damaged it will mend itself at once.



FIGS. 2,367 and 2,368.—General Electric bushing construction for distribution and small power transformers. Method of clamping porcelain bushings in transformer tank; fig. 2,368, cover bushing for moderately high voltage distribution transformer.

By providing good circulation for the oil, the transformer can get rid of the heat produced in it readily and operate at a low temperature, which not only increases its life but cuts down the electric resistance of the copper conductors and therefore the I^2R loss.

An important development in the construction of oil insulated transformers is the *oil conservator*, as shown in fig. 2,369. In this construction an auxiliary conservator tank, usually mounted on the transformer cover is connected to the main tank so that the main tank is always completely filled with oil and expansion of the oil is taken care of by the conservator. Thus the usual air space above the oil in the main tank is eliminated and due to the restricted opening between the two tanks, the oil in the conservator is at a very low temperature. Hence no decomposition or sludging of the oil can take place as it usually does in transformers where the hot oil is exposed to the air.

Pressure in the main tank is prevented by opening the conservator to the outside air through a breathing device. Any accumulation of moisture in the conservator is caught in a sump from which it may be drawn off. This construction eliminates "breathing" in the main tank and keeps the oil absolutely dry. It avoids explosions due to a possible mixture of air and gas formed from the hot oil. It furthermore greatly retards the rate of organic fibrous insulations.

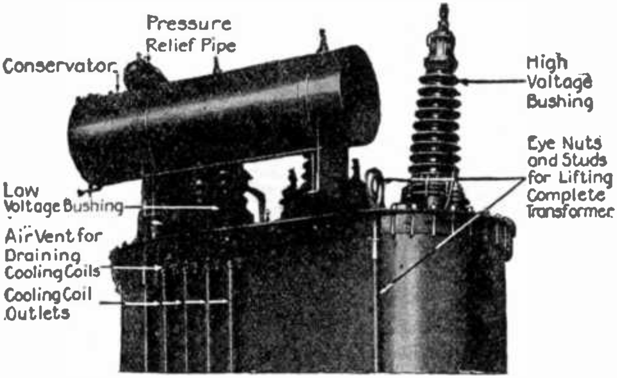
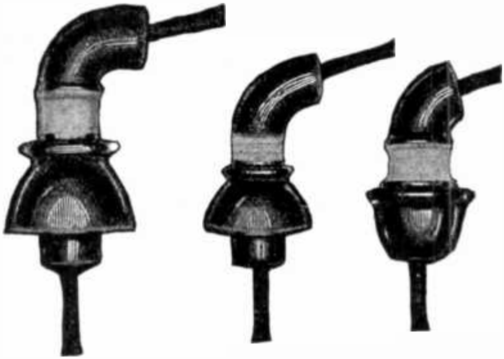


FIG. 2,369.—Top of General Electric three phase water cooled outdoor transformer with *oil conservator*.

Efficiency of Transformers.—The efficiency of transformers is *the ratio of the electric power delivered at the secondary terminals to the electric power absorbed at the primary terminals.*

Accordingly, the output must equal the input minus the losses. If the iron and copper losses at a given load be known, their values and consequently the efficiency at other loads may be readily calculated.

Example.—If a 10 kilovolt ampere constant pressure transformer at full load and temperature have a copper loss of .21 kilowatt or 2.1 per



FIGS. 2,370 to 2,372.—General Electric pocket type high voltage bushings for use on 19,250 to 551 volt lines.

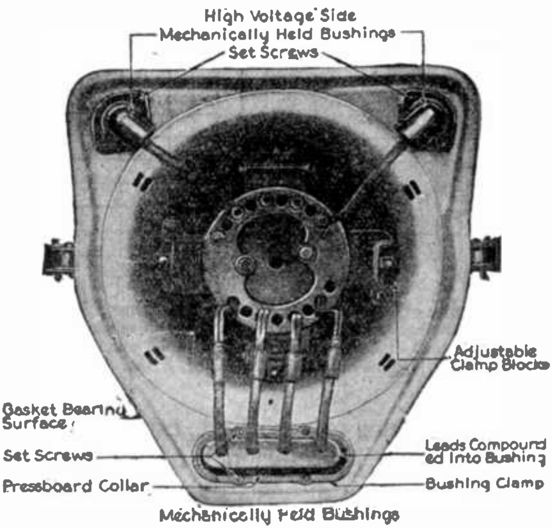


FIG. 2,373.—Top view of 2,300 volt distribution transformer showing location of core and coils in tank and method of clamping pocket bushing.

cent., and an iron loss of .09 kilowatt or .9 per cent., then its efficiency =

$$\frac{\text{output}}{\text{input}} = \frac{10}{10 + .21 + .09} \times 100 = 97.1 \text{ per cent.}$$

At three quarters load the output will be 7.5 *kva*. and as the iron loss is practically constant at all loads and the copper loss is proportional to the square of the load, the

$$\text{efficiency} = \frac{\text{output}}{\text{input}} = \frac{7.5}{7.5 + .12 + .09} \times 100 = 97.3 \text{ per cent.}$$

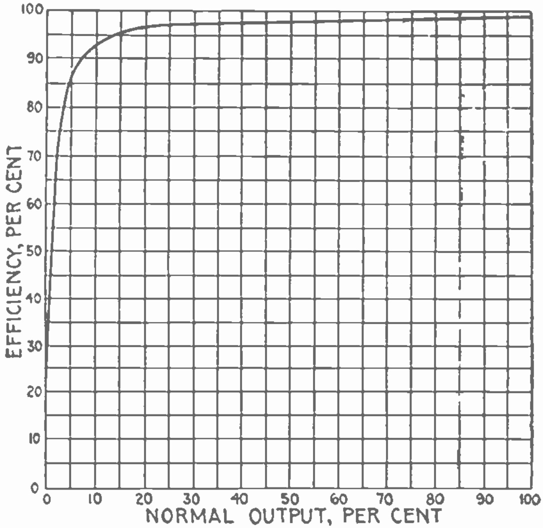
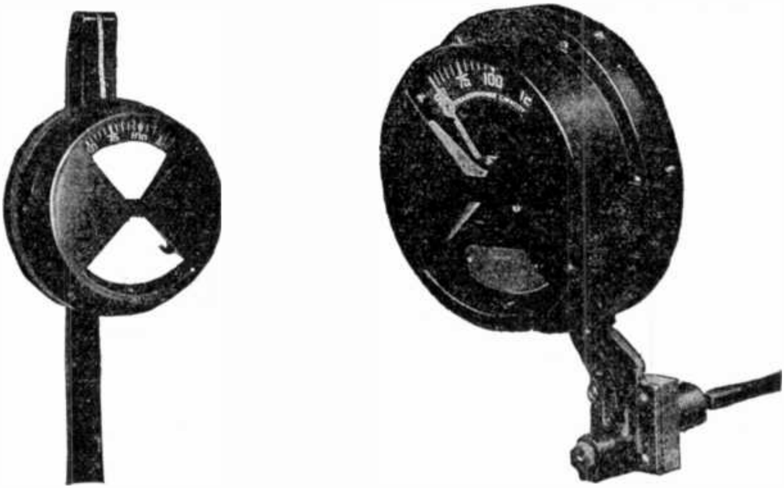


FIG. 2,374.—Efficiency curve of Westinghouse 375 *kw*. transformer. Pressure 500 to 15,000 volts; frequency 60. Efficiencies at different loads: full load efficiency, 98%; ¾ full load efficiency, 98%; ½ full load efficiency, 97.6%; ¼ full load efficiency, 96.1%; regulation non-inductive load, 1.4%; load having .9 power factor, 3.3%.

The matter of efficiency is important, especially in the case of large transformers, as a low efficiency not only means a large waste of power in the form of heat, but also a great increase in the difficulties encountered in keeping the apparatus cool. The efficiency curve shown in fig. 2,374, serves to indicate, however, how slight a margin actually remains for improvement in this particular in the design and construction of large transformers.

The efficiency of transformers is, in general, higher than that of other electrical machines; even in quite small sizes it reaches over 95 per cent., and in the largest, is frequently as high as 99 per cent.



FIGS. 2,375 and 2,376.—General Electric thermotel transformer load indicator for pole and subway service. Fig. 2,375 pole service type; fig. 2,376, subway service type. *It is used* for making load surveys on distribution systems which result in many advantages such as improved service, increased revenue and more economical operation. The thermotel consists essentially of two thermometers; one, of the capillary tube type, is immersed in the oil; the other, of the bimetallic type, is located in the external case and corrects for the ambient temperature. The combination actuates the hand and danger signal. The external case of the pole type instrument is made of brass, finished in black baking japan and thermally insulated from the radiant heat of the transformer by a metal screen and air space. The metallic supporting arm is riveted to the case. This arm also supports and protects the capillary tube and oil thermometer bulb.

To measure the efficiency of a transformer directly, by measuring input and output, does not constitute a satisfactory method when the efficiency is so high. A very accurate result can be obtained, however, by measuring separately, by watt meter, the core and copper losses.

The core loss is measured by placing a watt meter in circuit when the transformer is on circuit at no load and normal frequency.

The copper loss is measured by placing a watt meter in circuit with the primary when the secondary is short circuited, and when enough pressure is applied to cause full load current to flow.

If it be desired to separate the load losses from the true I^2R loss, the resistances can be measured, and the I^2R loss calculated and subtracted from the watt meter reading. The losses being known, the efficiency at any load is readily found by taking the core loss as constant and the copper loss as varying proportionally to the square of the load. Thus,

$$\text{efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100$$

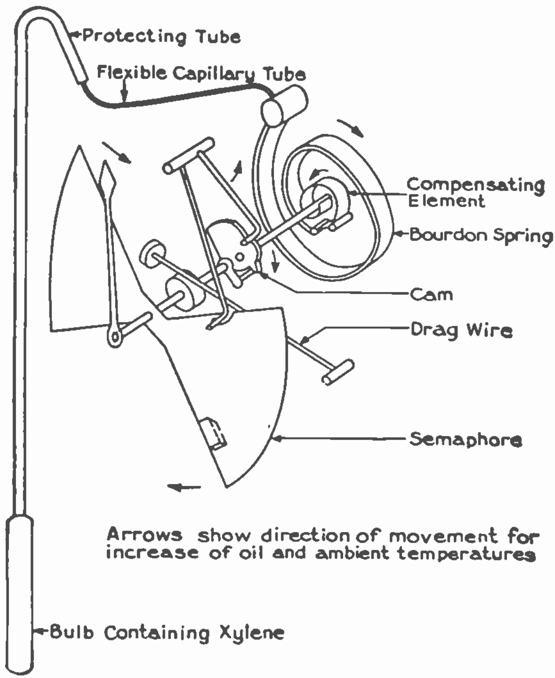


FIG. 2,377.—General Electric thermotel mechanism. *It consists of* two thermometers connected in series; one, of the capillary tube type, is immersed in the oil; the other, of the bimetallic type, is located in the external case and corrects for the ambient temperature. The combination actuates the hand and danger signal as shown in the figure.

All Day Efficiency of Transformers.—This denotes the ratio of the total watt hour output of a transformer to the total watt hour input taken over a working day. To compute this efficiency it is necessary to know the load curve of the transformer during a day. Suppose that for a small lighting transformer this

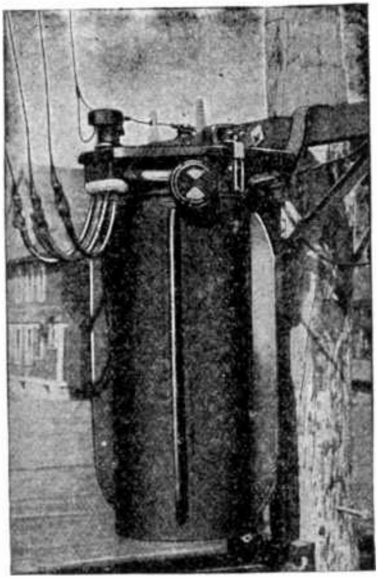


FIG. 2,378.—Installation of General Electric pole type thermotel. The hand is of the maximum reading type and records the maximum percentage of transformer capacity which has been utilized since the last resetting. This capacity is the actual capacity of the transformer as limited by the internal winding temperature (hot spots). An indication of 100% or less may be well above the name plate rating of the transformer in cold weather. Also, short time peak loads such as are normally carried by distribution transformers, are recorded in terms of continuous output.

is equivalent to 5 hours at full load, and 19 hours at no load. Then, if W_1 be the core loss in watts, W_2 the copper loss at rated load, and W, the rated output,

$$\text{output} = 5 \times W,$$

$$\text{losses} = 5\,(W_1 + W_2) + 19\,W_1,$$
$$\text{input} = 5\,(W + W_1 + W_2) + 19\,W_2$$

and the all day efficiency is equal to

$$\frac{5\,W \times 100}{5\,(W + W_1 + W_2) + 19\,W_1} \text{ per cent.}$$

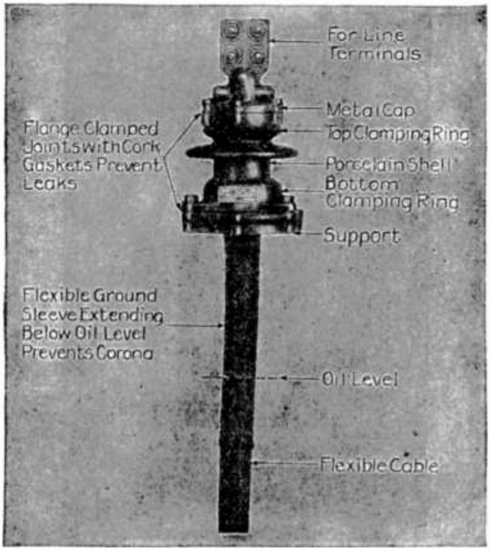


FIG. 2,379.—General Electric solid type single conductor bushing with flexible cable, type S, form F. *Rating* 7,500 volts, current up to 3,000 amperes. The bushing is equipped with fixed terminal couplings at both ends of the flexible cable conductor, thus requiring disconnection at the lower end before removal from the transformer. It is fitted with a wrapped wire ground sleeve preserving the flexibility of the cable and is designed for use under oil pressure as in conservator type transformers. Suitable for either indoor or outdoor installation.

Commercial or all day efficiency is a most important point in a good lighting transformer.

The principal factor in securing a high all day efficiency is to keep the core loss as low as possible. The core loss is constant—it continues while current is supplied to the primary, while copper loss takes place only when the secondary is delivering energy.

FIGS. 2,380 to 2,384.—General Electric solid type transformer bushings for voltages up to 73,000. A Herkolite core surrounding a metal tube is the basis of this bushing structure and supplies the required strength against puncture. A grounded metal sleeve surrounding the center portion of the core and extending from the cover of the tank to a point below the oil level, prevents corona in the air space above the oil at all voltages. The petticoated porcelain shell is complete in one piece, having no joints to be cemented or to leak. This provides the necessary creepage strength against flashover. Between the ends of the porcelain and the adjacent metal fittings, the joints are made oil tight with composition cork gaskets. *In assembling* the bushings, the space between the core and porcelain is filled with a solid insulating compound which is oil proof and permanent. The joint between the supporting ring of the bushing and the cover of the tank is fitted with a special gasket, making an oil tight joint. The conductor, consisting of a cable passing through the center metal tube, may be disconnected at the upper end of the bushings to permit the removal of the bushing without entering the tank.

NOTE.—*The importance of transformer bushings* has been emphasized in recent years because of the present day call for reliability and continuity of service. This means bushings with adequate safety factors against normal and abnormal voltages of operating frequency under all climatic conditions; and as great a degree of protection as possible in the design itself, against lightning and other high frequency disturbances. Transformer bushings not only withstand voltages above those to which the circuit is limited by the lightning protection usually afforded, but also provide relief from abnormal voltage stresses by flashing over to ground before there is danger of insulation breakdown either in the transformer or the bushing. The bushings differ in shape and size with the voltage and in all cases are designed for the particular service requirements of the transformers in the different voltage classes to which they are applied.

In general, if a transformer is to be operated at light loads the greater part of the day, it is much more economical to use one designed for a small iron loss than for a small full load copper loss.

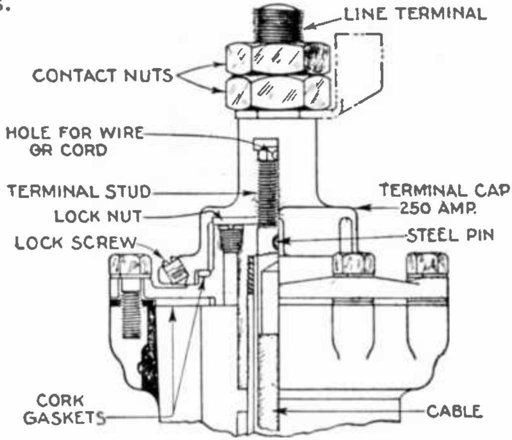
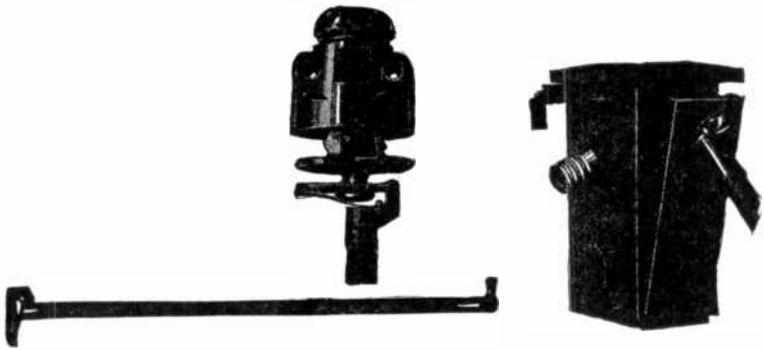


FIG. 2,385.—Terminal detail of General Electric solid interchangeable bushing.

FIGS. 2,386 to 2,388.—General Electric insulator type fusible plug cutout. This type is rated 30 amperes at 2,500 volts; and 15 amperes at 3,500 volts. These cutouts which are usually mounted directly on the cross arm by means of two wood screws, consist of a dark brown glazed porcelain receptacle, containing spring clips to which the line leads are connected, and a porcelain plug with nickel plated blades on which the fusible element is fastened. These blades have projections which engage in locking devices in the base, holding the plug firmly in position and preventing the connection being broken or the plug dropping out, due either to jarring or to the blowing of the fuse. Fuse links of all the convenient ratings from 1 to 30 amperes are available, designed particularly for this cutout. These special fuse links should always be used because they have the proper design characteristics for most successful operation of the cutout.



FIGS. 2,389 to 2,391.—General Electric plug puller and method of operation. It is used to replace a fuse when necessary. On the end opposite the plug puller is a standard switch hook which may be used to operate the other General Electric primary cutouts and switches on lines up to 7,500 volts.

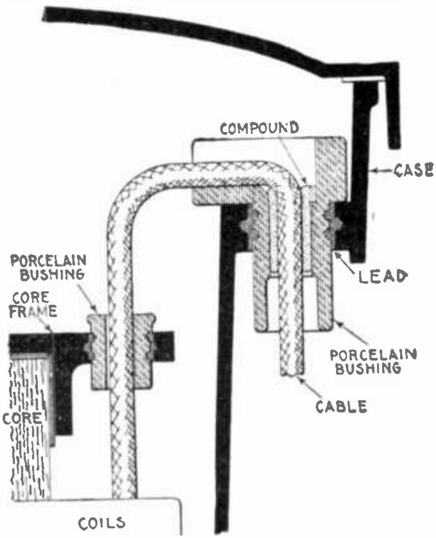
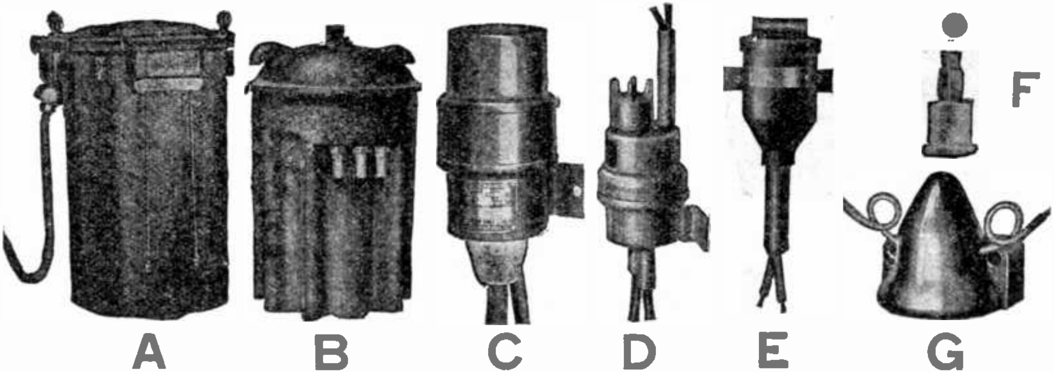


FIG. 2,392.—Method of bringing out the secondary leads in Wagner central station transformers. Each primary lead is brought into the case through a similar bushing. Observe the elimination of all possibility of grounding the cable on the case or core.

Transformer Cutouts or Fuse Boxes.—Fusible primary cutouts, sometimes called transformer fuse boxes, are placed in the high voltage circuit of transformers to protect the windings from overloads and short circuits. They are usually single pole devices and one is placed in each incoming line.



Figs. 2,393 to 2,399.—General Electric type SL series transformer and protective device for street lighting service. This type transformer is designed to supply current to one or a small number of lamps connected in series and located where the high pressure of the ordinary constant current series circuit would be objectionable. The field for this transformer necessarily lies in the vicinity of constant current series circuits as it is designed to operate from a circuit where the current is held constant. Certain classes of lighting require lower voltage than that obtainable from series arc or incandescent circuits and to provide for this, companies would be compelled to run parallel circuits from the central station, often at a considerable expense. if series transformers were not employed. *In operation,* the primary winding is connected in series with the main series circuit so that, under all conditions of load on the secondary, the primary carries the full current of the main circuit which is maintained at its normal value by a constant current regulating device. *Current regulation,* when the load is reduced to 80% of its normal rating, the secondary current will not increase more than 1% above its full load value, with rated primary current and frequency. These transformers are not designed to carry overloads. *In operation,* the transformers are built as air cooled units in sizes up to and including 4 *kva.*, 60 cycles, and as oil cooled transformers for all larger sizes. In the pole type transformers, both primary and secondary leads are brought out through a single heavy porcelain bushing which is designed for ample mechanical as well as electrical strength. In the subway type, the primary leads are brought out through separate wiping sleeves at the lower end and the secondary leads through a single wiping sleeve at the top. Other arrangements are special but can be made if required. *In construction,* the protective devices are designed with clips to short circuit the secondary system when the handle is removed. A second pair of clips in the handle hold the films. The films consist of plates of soft metal cemented to the two sides of a fibre disc through which a hole is pierced. The thickness of the fibre determines the strength of the air gap which, being protected, is very uniform. When the gap breaks, the metal flows and fills the hole so as to form a short circuit across the transformer. When the handle containing the film is inserted in the holding clips the protective device

All types depend on overload current melting a fusible metallic strip to open the circuit. Various methods of extinguishing the resulting arc are employed, the most common of which is the expulsion action caused by the heated gases being confined in a tube with a small opening. The velocity of the escaping gas is thus increased, tending to clear the tube of arc sustaining vapors.

Constant Current Transformers for Series Lighting.—The principle of the constant current transformer as used for series lighting is readily understood by reference to the elementary diagram shown in fig. 2,400.

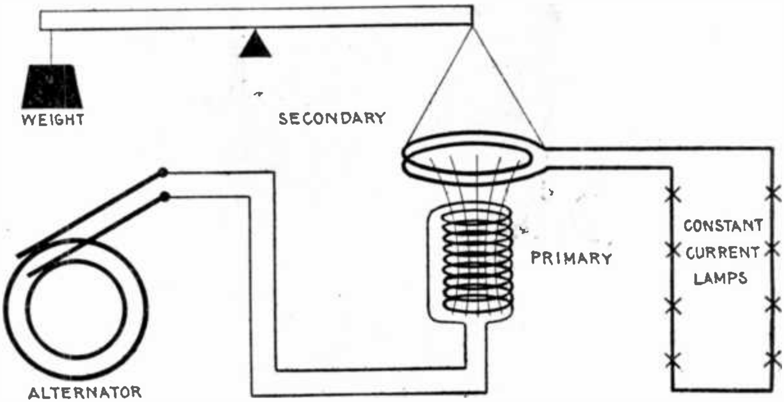


FIG. 2,400.—Elementary diagram illustrating the principles of constant current transformer as used for series arc lighting.

A constant alternating current is supplied to the stationary primary coil which induces a current in the movable secondary coil. The pressure induced in the coil will depend on the number of lines of flux which pass through it and by changing its position in the magnetic field over the primary a variable voltage

FIGS. 2,393 to 2,399.—*Text continued.*
circuit is opened and the film left in position to operate in case the system is open circuited. A, pole type oil filled 5 to 10 *kw.*; B, subway type oil filled 5 to 10 *kw.*; C, pole type transformer, less than 5 *kw.*; D, subway type transformer with self contained protective device, less than 5 *kw.*; E, subway type protective device; F, automatic film cut out; G, pole type protective device.

can be produced and a constant current maintained in the lighting circuit when the lamps are turned on or off, or if the resistance of the circuit be lowered by the consumption of carbons.

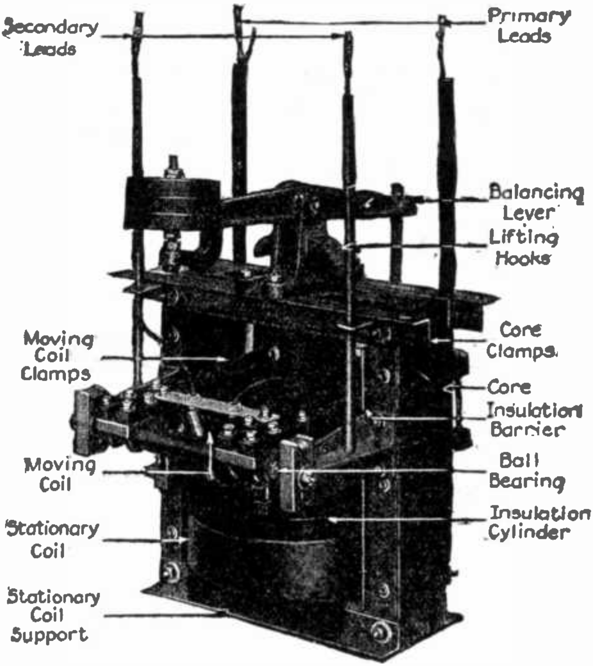


FIG. 2,401.—General Electric polyphase Novalux constant current transformer. ***In operation,*** one side of the moving coil, or secondary, is supported by a ball bearing hinge, while the opposite side is linked to a counter-balanced lever. The core and coils are supported as a removable unit on angle iron brackets welded to the inside of the tank, and the cover can be readily removed for inspection or adjustment purposes. The primary and secondary leads enter the tank through porcelain bushings of the mechanical type which resemble those of the standard pole type distribution transformer.

Since the induced currents in the secondary are repelled by the primary there is a tendency for the secondary coil to jump out of the primary field, and in case of a very large current due to a short circuit in the lamp circuit, the secondary current is quickly reduced to normal by the rapid movement of the coil upward.

By adjusting the counterweight for a given number of amperes required by the load, the current will be maintained constant by the movement of the secondary coil.

The magnetic field produced by the primary must be kept the same by a constant current from the alternator, therefore, when the lamp load is increased the primary voltage increases similar to that of an ordinary

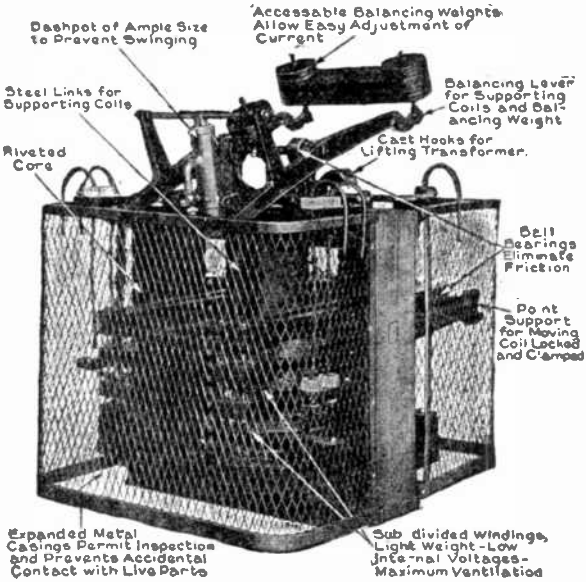


FIG. 2,402.—General Electric automatic station type Novalux constant current transformer. *In construction,* one side of the secondary coil is mounted on a ball bearing hinge, and the opposite side linked to a counter balanced lever. The movement of the secondary coil is damped by means of an oil filled dash pot. The position of the counter balance weights is fixed to give the rated secondary current. The transformer has a high inherent reactance which protects the lamps; for instance, if there be but one lamp on the secondary circuit, the current surge upon automatic starting wil. not be sufficient to destroy the filament. The windings have vertical ventilating ducts.

series wound direct current dynamo. In other words the alternator and regulating transformer supply a constant current and variable voltage.

Constant current incandescent lighting systems for use in small towns also use this method for automatically regulating the current.

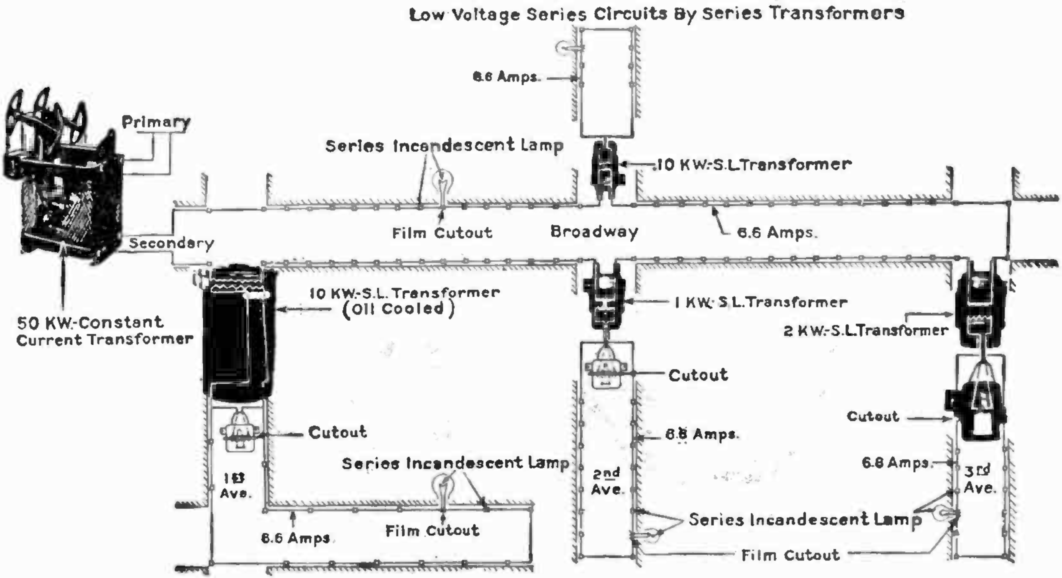


FIG. 2,403.—Diagram showing low voltage series circuits with General Electric series transformers. Some of this lost voltage lighting is supplementary to the regular street lighting system and filling the same function, it is desirable to control it simultaneously with the street lights. The transformer affords the ideal method for this control as the low voltage circuit is turned on and off with the closing or opening of the main constant current transformer circuit. When the primary circuit is long and unprotected except at the constant current transformer supplying the circuit, lightning arresters may be considered advisable for protection of the series transformers. Two lightning arresters would be required, one on each side of the primary coil, and they must be of the same rating as demanded for the main series circuit. In general, the secondary circuit is short and not subject to lightning disturbances. The only protective feature usually required is the protective device to prevent open circuit operation of the transformer in event of circuit trouble. Should the nature of the secondary circuit require protection, the rating of the lightning arrester would depend on the open value of the series transformer.

Regulation.—This term applies to the relative change of pressure (or current) with changing load. In the transformer, regulation is inherent, that is, it automatically tends to maintain constant voltage (or current). Regulation may be defined more precisely as *the percentage increase in the secondary voltage as the load is decreased from its normal value to zero.* Thus, observation should be made of the secondary voltage, at full load and at no load, the primary pressure being held constant at the normal value.

The regulation is said to be "good" or "close," when this change is small. In the design of a transformer for a given efficiency, good regulation and low iron losses are in opposition to one another when the best results are

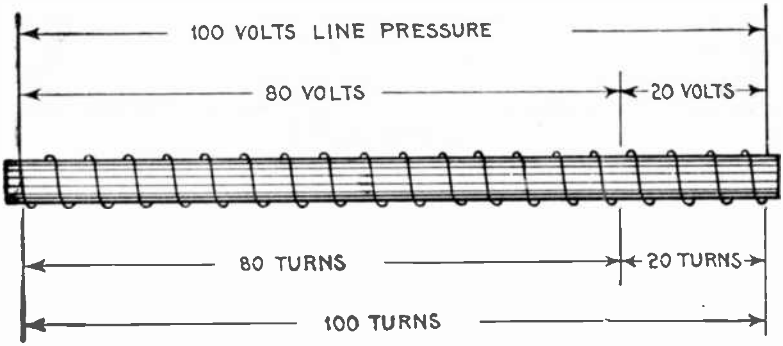
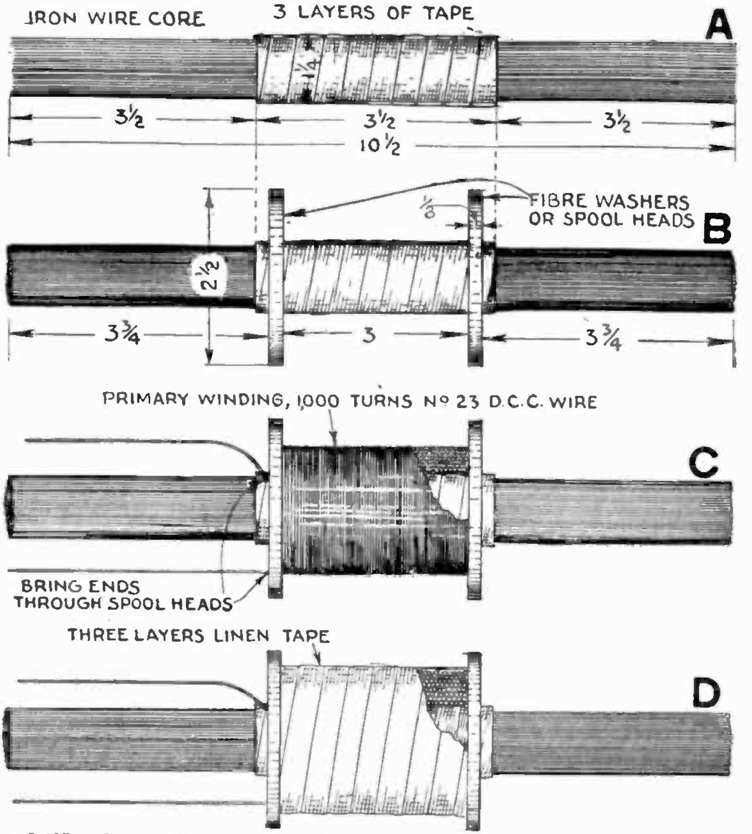


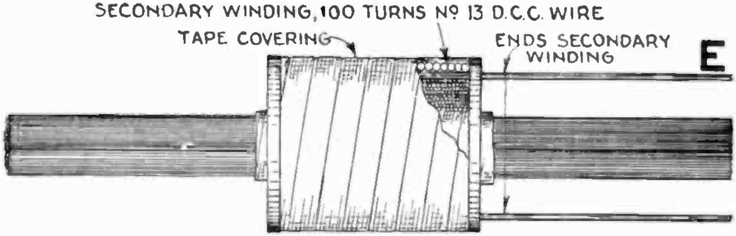
FIG. 2,404.—Diagram illustrating connections and principles of auto-transformers as explained in the accompanying text.

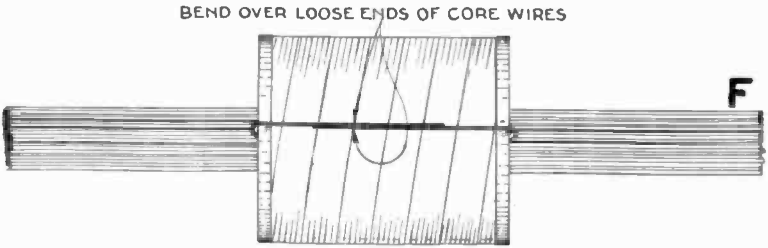
desired in both. A well designed transformer, however, should give good results, both as to regulation and iron losses, the relative value depending upon the class of work it has to do, and size.

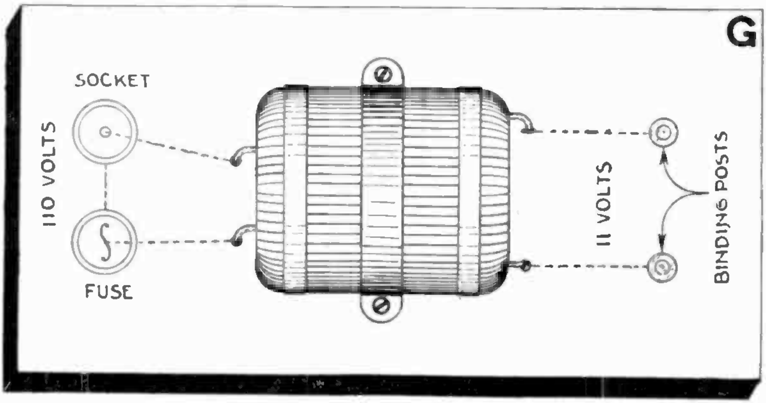
Auto-transformers.—In this class of transformer, there is only one winding which serves for both primary and secondary. On account of its simplicity it is made cheaply.



FIGS. 2,405 to 2,411.—***How to Build a Bell Ringing Transformer.***—1, build up a core of soft iron wire (any gauge between 16 and 24) and cover the central portion with three layers of insulating tape as in fig. **A**; 2, thread on two fibre washers or spool heads as in fig. **B**, the washers to be a very tight fit; treat heads and tape with a coat of good shellac varnish and bake until dry and hard, being careful to get no shellac between the wires of the core ends; 3, for the primary winding, wind 1,000 turns No. 23 double cotton covered (*d.c.c.*) wire, bringing out the ends as in fig. **C**; 4, wind over primary winding three layers of linen tape as in fig. **D**, cover with shellac and bake; 5, for the secondary winding, wind 100 turns of No. 13 double cotton covered wire and cover with tape as in fig. **E**, bringing out the ends as shown; 6, bend the loose ends of the core wire over the outside of the secondary winding, the start of this operation being shown in fig. **F**. When completed these wires form an iron wire shell surrounding the whole coil. Three strips of tape serve to bind the wires in place; 7, the transformer is fastened to a base board by means of a brass strap as







FIGS. 2,405 to 2,411.—*Text continued.*

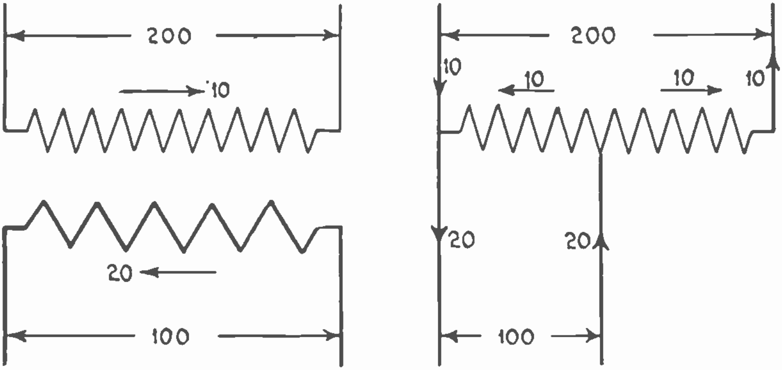
in fig. G. Place insulating tape under the brass strap. Fig. G, also shows method of arranging the connections. The allowable primary current is about ½ ampere, the secondary current on full load will be five amperes. The transformer will consume as much energy as one ordinary sixteen candle incandescent lamp. This transformer is designed for 60 cycles, because that frequency is commonly used. For 25 cycles the core should be 1¾ ins. in diameter; for 133 cycles it should be one inch. The winding in each case would be the same.

Auto-transformers are used where the ratio of transformation is small, as a considerable saving in copper and iron can be effected, and the whole transformer reduced in size as compared with one having separate windings.

Fig. 2,404 illustrates the electrical connections and the relations between the volts and number of turns.

By using the end wire and tapping in on turn No. 20 a current at 20 volts pressure is readily obtained which may be used for starting up motors requiring a large starting current and yet not draw heavily on the line.

Since the primary is connected directly to the secondary it would be dangerous to use an auto-transformer for lighting service. This type of



Figs. 2,412 and 2,413.—Two winding transformer and single winding or auto-transformer. Fig. 2,412 shows a 200:100 volt transformer having a 10 amp. primary and a 20 amp. secondary, the currents being in opposite directions. If these currents be superposed by using one winding only, the auto-transformer shown in fig. 2,413 is obtained where the winding carries 10 amp. only and requires only one-half the copper (assuming the same mean length of turn). If R, be the ratio of an auto-transformer, the relative size of it compared with a transformer of the same ratio and output is as $\frac{R-1}{R}$: 1. *For example,* a 10 *kw.* transformer of 400 volts primary and 300 volts secondary could be replaced by an auto-transformer of $10\times\frac{1.33-1}{1.33}=2.5$ *kw.*; or, in other words, the amount of material used in a 2½ *kw.* transformer could be used to wind an auto-transformer of 400 : 300 ratio and 10 *kw.* output.

transformer is used usually as a compensator for motor starting boxes, for balancing three-wire systems and for tying two power systems of different voltage.

Current and Pressure (Potential) Transformers.—There are two general classes of these transformers:

1. Tripping transformers;
2. Instrument transformers.

By the use of current and pressure transformers, low voltage circuits are obtained with characteristics in practical agree-

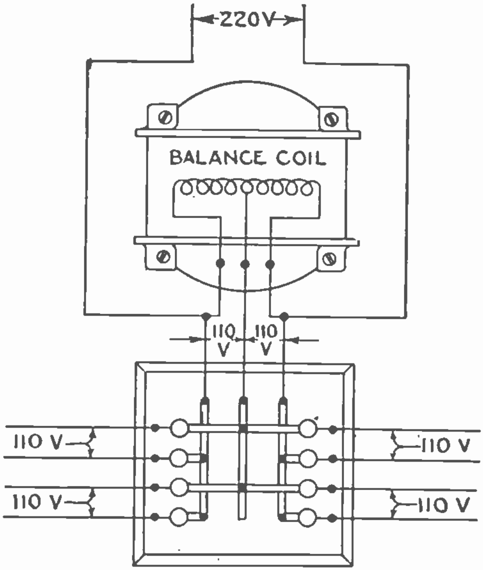
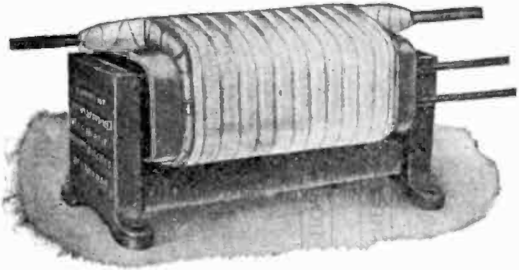


FIG. 2,414.—Sorgel air cooled 220-110 volt auto transformer or balance coil. *Used principally* to convert 220 volt *a.c.* power circuits to 110 volt for lighting, portable appliances or small motors. The *kva.* rating of balance coils is the unbalance load capacity. Where the unbalance is not known, it is usual practice to install a balance coil with a capacity of approximately 25% of the total load connected to the coil. *For example,* if the connected load be four kilowatts, install a one *kva.* balance coil.

ment with the high voltage circuit. Current transformers are extensively used to obviate the necessity of carrying large or high voltage conductors to instruments and protective devices.



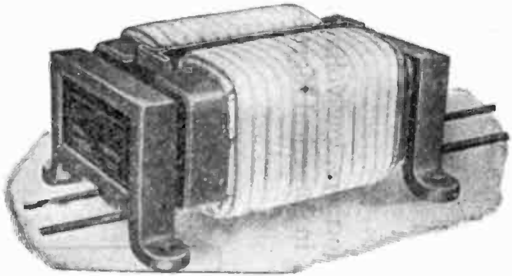


FIG. 2,415.—Moloney small current transformer, five ampere secondary, with primary as high as 300 amperes.
FIG. 2,416.—Moloney small low voltage transformer rating up to 600 volts high with $\frac{110}{220}$ volts low.

FIG. 2,417.—Moloney variable voltage transformer 110 volts high. By means of two rotary dials low voltage of 1 to 150 in 1 volt steps may be obtained.

FIG. 2,418.—Moloney small potential transformer supplied in voltages up to 4,400 high and 110 low.

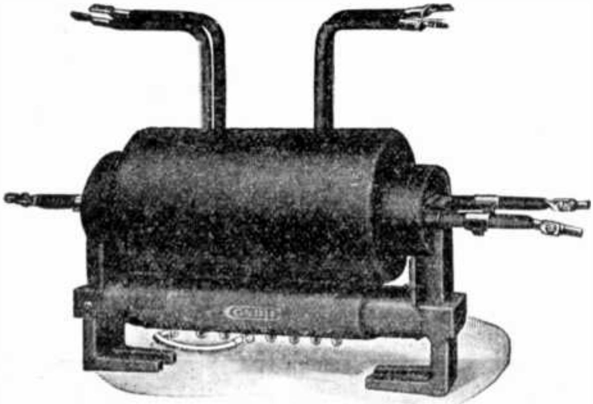


FIG. 2,419.—Condit current transformer maximum volts 15,000; amperes 5 to 800; cycles 25 to 60; double ratio. It may be used in any combination of instruments, trip coils, or relays where the secondary load does not exceed 40 volt amperes with 5 amperes flowing in the secondary circuit at 60 cycles and 20 volt amperes at 25 cycles.

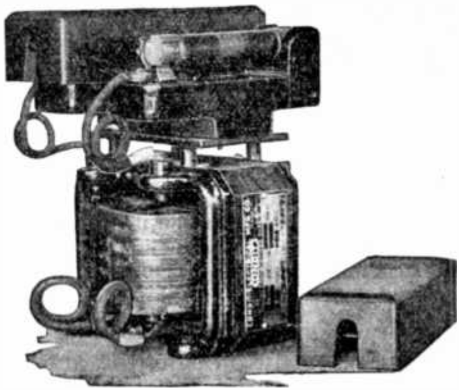


FIG. 2,420.—Condit pressure (potential) transformer. Maximum volts, dry insulated 4,400. Maximum volts, oil insulated 13,200, 25 or 60 cycles, for use in connection with under-voltage trip attachments and *a.c.* instruments, also suitable for use in connection with industrial or switchboard work.

An instrument transformer is a device *suitable for use with measuring instruments in which the conditions of current, pressure and phase in the primary or high voltage circuit are represented with acceptable accuracy in the secondary or low voltage circuit.*

While accuracy is of vital importance, it is essential in current transformers that their construction be such as to withstand momentarily short circuit currents many times their rated carrying capacity without injury. Furthermore, it is of great importance that the design afford a high degree of insulation. Tripping coils of protective devices usually impose a heavy "burden" upon current transformers.

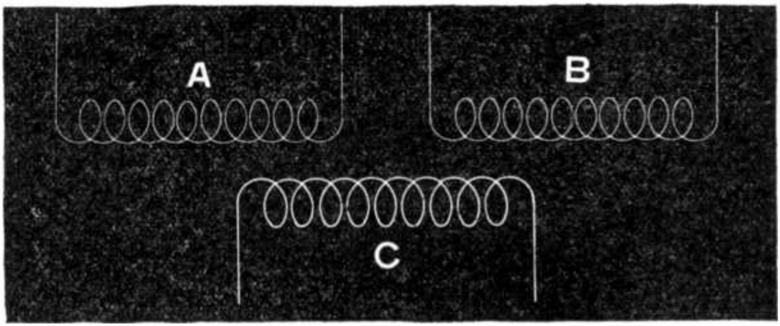


FIG. 2,421.—Diagrammatic sketch of one phase of a three winding transformer.

Where extreme accuracy is required, it is recommended that separate instrument transformers be used to supply energy to instruments or meters, and that tripping transformers be used in connection with trip coils of protective devices. The construction of both tripping and instrument transformers may be classified as air insulated and oil insulated.

Three Winding Transformers.—The gradual growth of transmission systems has not only brought the art to the stage of high voltage systems requiring large capacity transformers to handle the immense blocks of power economically, but has also resulted in high voltage networks that must be tied together in order that power may be interchanged between them. In some cases three sections, operating at different voltages, are tied together by means of one bank of transformers. This requires three winding transformers so designed that power may flow in any combination of ways between the three sections and not suffer prohibitive voltage regulation.

In practically all extensive high voltage systems of to-day, regulation of voltage at certain points is provided by means of synchronous condensers. These condensers are connected to the high voltage system through transformers and in order to produce maximum economy in apparatus, in many cases the condenser connection is made through a third winding in the transformers, tying two sections of the system together.

The requirements of a transformer for this service are somewhat different from those where power may flow in various directions. Here the reactance between the condenser winding and the winding which feeds the system section from which the condenser draws its wattless power should be moderately low, so as to throw an excessive burden on the excitation range of the condenser. At the same time the reactance between it and the other two windings should be high enough to prevent excessively large short circuit currents in case of fault between the transformer and the condenser.

Another application of three winding transformers is where two systems, or two sections of a system are to be tied together in such a manner that the phase positions of the two sections are identical and at the same time provide a neutral connection for the system, thus requiring star connection on both power windings. The third windings, in such cases, are connected in delta and are generally referred to as tertiaries.

Transformer Oil Dryer and Filter.—The deleterious effect of small amounts of moisture on the dielectric strength of oil is now well understood, and it appears to be even more serious than is generally supposed. In fig. 2,422, the curve shows clearly the great reduction in dielectric strength produced by the presence of water in very small amounts. As shown, the moisture content must not exceed .0008 per cent. (eight parts in 1,000,000) in order to obtain a dielectric strength of 22,000 volts in the standard test (.1 in. between the terminals) as required for all high tension work.

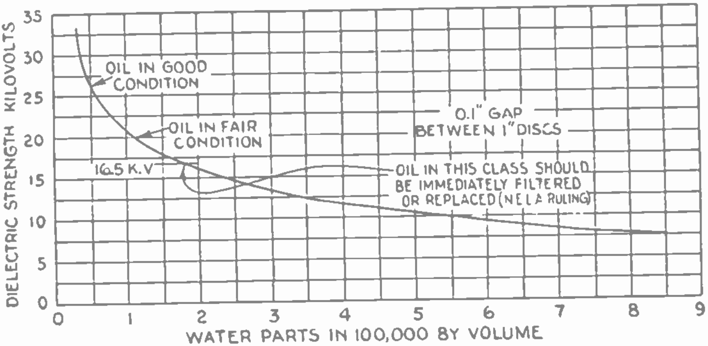


FIG. 2,422.—Curve showing the great reduction in dielectric strength produced by the presence of water in amounts up to 8 parts in 100,000.

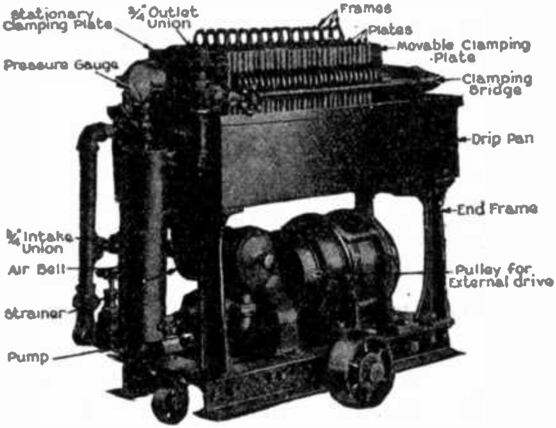


FIG. 2,423.—General Electric transformer oil dryer and filter for freeing the oil from moisture, slime and sediment. *In operation*, the oil is forced through several layers of dry blotting paper. The complete equipment consists of a filter press with motor driven oil pump, electric drying oven for thoroughly drying the filter paper before placing it in the press.

Fine dust, especially if metallic, is almost as effective as water in reducing the dielectric strength. Sediment, which may result from long continued heating, should also be removed in order to preserve the normal viscosity of the oil and to prevent accumulations on interior parts of the transformer and possible clogging of the oil channels.

An efficient method frees the oil from moisture, slime and sediment by forcing it under pressure through several layers of dry blotting paper in a specially designed filter press. The paper is free from chemicals, foreign substances and coloring matter, and is furnished cut to exact size to fit the filter. The solid matter in the oil is caught by the paper, while the water is retained by capillary action. The capillary attraction between the paper and water is greater than that between the paper and the oil and effectiveness of the method is mainly due to this fact. One treatment is generally sufficient to produce a dielectric strength of 28,000 volts, corresponding to a water content of only one part in about 250,000. A purity greater than this is of no practical benefit as it cannot be maintained with the oil in regular use.

Effects of Operating Conditions on Transformer Performance.—The effects due to changes in operating conditions as here given should be noted.

Effects of Change in Voltage

Iron Loss. The iron loss varies approximately as the square of the voltage.

Copper Loss. The copper loss also varies as the square of the voltage, but decreases with an increase in voltage; assuming a constant kilovolt ampere output.

Efficiency. The efficiencies of distribution type transformers at fractional loads will decrease with an increase in voltage, while the efficiencies at full load or overloads will increase with an increase in voltage and vice versa.

Regulation. The regulation will vary as the square of the voltage, but will decrease with an increase in voltage, assuming a constant kilovolt ampere output.

The following table shows approximate variations in the performance of distributing transformers with variations in voltage assuming a constant output.

Voltage	Iron Loss per cent.	Copper Loss per cent.	Regulation per cent.
2,200	91	109	109
2,300	100	100	100
2,400	109	91	91

Heating. Iron temperatures increase and copper temperatures decrease with an increase in voltage, and vice versa, for a constant kilovolt ampere output.

Effects of Changes in Frequency

Iron Loss. The iron loss will increase with a decrease in frequency. A 60 cycle transformer will have approximately 11% higher iron loss when operated at 50 cycles than at 60 cycles., The iron loss of a 60 cycle transformer operated on 25 cycles is so high as to make such a practice impossible. It is, however, possible to operate a 25 cycle unit on 60 cycles and in this case the iron loss will be decreased 25%.

Copper Loss. In distribution transformers the copper loss is practically independent of the frequency.

Efficiency. Since the copper loss is not affected by a decrease in frequency, a given transformer efficiency will be less at a low frequency than at a high one.

Regulation. The regulation at 100% power factor is not affected appreciably by a change in frequency since ohmic drop is independent of frequency. The reactance drop is so affected. however, and the regulation at low power factors will decrease with a decrease in frequency and vice versa. Thus the regulation of a 25 cycle transformer, when operated on 60 cycles and at low power factors, will be very much poorer than when operated at 25 cycles.

Heating. As the total loss is greater at a low frequency than at a high one, the temperature will be correspondingly increased

Effect of Changes in Wave Form

Performance data is based upon operation on circuits having a pressure sine wave. A peaked wave will give lower values of iron loss, while a flat top wave will give higher values of iron loss than those given in the tables, with corresponding Increase and decrease in efficiency. Copper loss and regulation are practically independent of wave form, while the heating is slightly less on circuits having a peaked wave and slightly greater on circuits having a flat wave than on those with a sine wave.

TEST QUESTIONS

1. *What is a transformer?*
2. *State the basic principle on which transformers operate.*
3. *What is the difference between a primary and secondary winding?*
4. *Upon what does the induced voltage depend?*
5. *When there is no load on the transformer, does any current flow?*
6. *What is the difference between the magnetizing current and the no load current?*

7. *Describe the action of the transformer with load.*
8. *Give a classification of transformers.*
9. *What is the difference between a step up and a step down transformer?*
10. *What is the difference between a core and snell transformer?*
11. *Describe a distributed core transformer.*
12. *Is it necessary to use a polyphase transformer to transform a polyphase current?*
13. *Name two varieties of polyphase transformer.*
14. *What are the various transformer losses?*
15. *Define hysteresis.*
16. *On what does hysteresis depend?*
17. *What mode of construction is adapted to avoid eddy currents?*
18. *Why does a transformer take current when the secondary circuit is open?*
19. *Which are the more important, the iron or copper losses, and why?*
20. *How may the iron losses be reduced to a minimum?*
21. *Name some methods of cooling transformers.*
22. *What is the behavior of a transformer with respect to heating when operated continuously at full load?*
23. *Why is a high rise of temperature objectionable?*
24. *Describe a natural draught air cooled transformer.*
25. *How much air is ordinarily used for cooling per kw. of load?*
26. *Explain the circulation of oil in an oil cooled transformer.*

27. *In what other capacities besides that of cooling agent, does the oil act?*
28. *What is an objection to oil?*
29. *How is a water cooled transformer cooled?*
30. *How much circulating water is required?*
31. *In water cooled transformers how much cooling surface is required for the cooling coil?*
32. *What is the* major *and* minor *insulation?*
33. *What is the most efficient insulating material for transformers?*
34. *Define the term "efficiency of transformers" and give example.*
35. *How is a transformer efficiency curve constructed?*
36. *What is the all day efficiency of a transformer?*
37. *What are transformer bushings used for?*
38. *Describe a constant current transformer.*
39. *Define the term* regulation.
40. *What is an auto-transformer?*
41. *What is the difference between current and pressure (potential) transformers?*
42. *Describe a three winding transformer.*
43. *How is oil treated for transformers?*

CHAPTER 53

Transformer Connections

Transformer Connections.—The alternating current has the advantage over direct current, in the ease with which the pressure and current can be changed by different connections of transformers.

On single phase circuits the transformer connections can be varied to change current and pressure, and in addition on polyphase circuits the phases can also be changed to almost any form.

Single Phase Connections.—The method of connecting ordinary distribution transformers to constant pressure mains is shown by the elementary diagram, fig. 2,426, where a transformer of 10 to 1 ratio is indicated with its primary winding connected to a 1,000 volt main, and a secondary winding to deliver 100 volts.

Fig. 2,424 shows a transformer with each winding divided into two sections. Each primary section is wound for 1,000 volts, and each secondary section for 50 volts. By connecting the entire primary winding in series, the transformer may be supplied from a 2,000 volt main, as indicated, and if the secondary winding be also connected all in series, as shown, the no load voltage will be 100 between the secondary terminals.

The sections of the primary winding may be connected in parallel to a 1,000 volt main, and 100 volts obtained from the secondary, or the primary and secondary windings may be connected each with its two sections in parallel, and transformations made from 1.000 to 50 volts as represented in fig. 2,425.

Paralleling Transformers.—Two or more transformers built to operate at the same pressure and frequency may be connected together in a variety of ways; in fact, the primary and

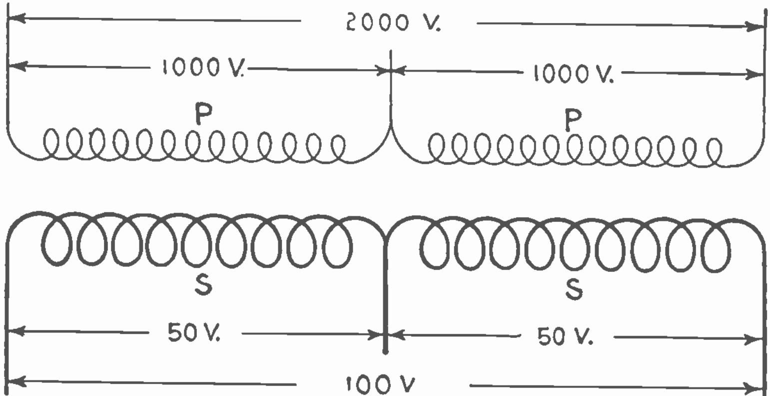


FIG. 2,424.—Diagram of single phase transformer having primary and secondary windings in two sections, showing voltages per section with series connections.

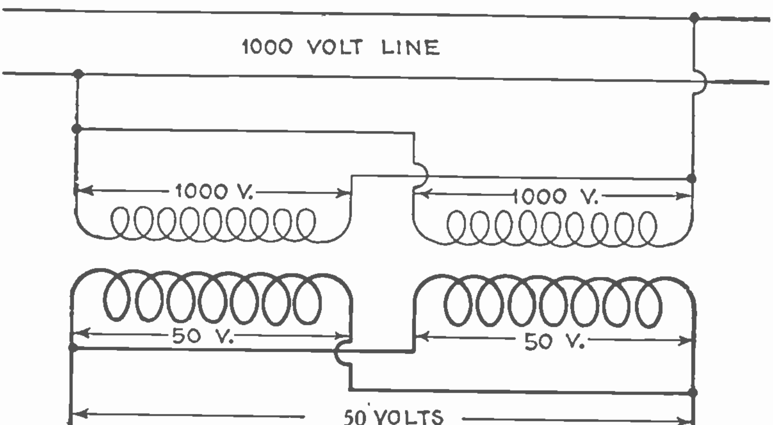
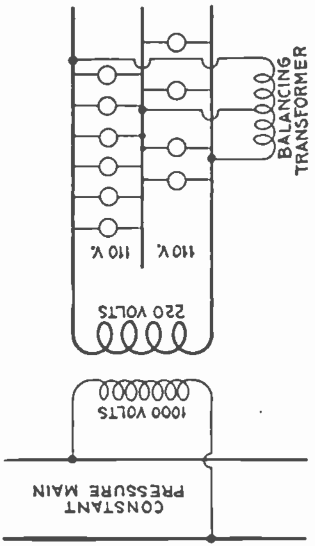


FIG. 2,425.—Diagram of single phase transformer with primary and secondary windings of two sections each, showing voltages per section with parallel connection.



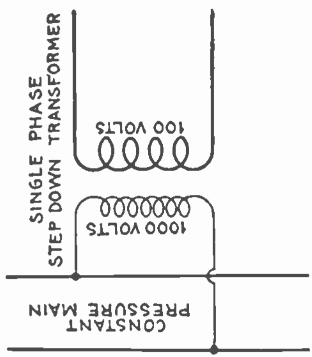


FIG. 2,426.—Single phase transformer connection with constant pressure main.

FIG. 2,427.—Usual method of single phase transformer connections for residence lighting with three wire secondaries. A balancing transformer is connected to the three wire circuit near the center of distribution as shown.

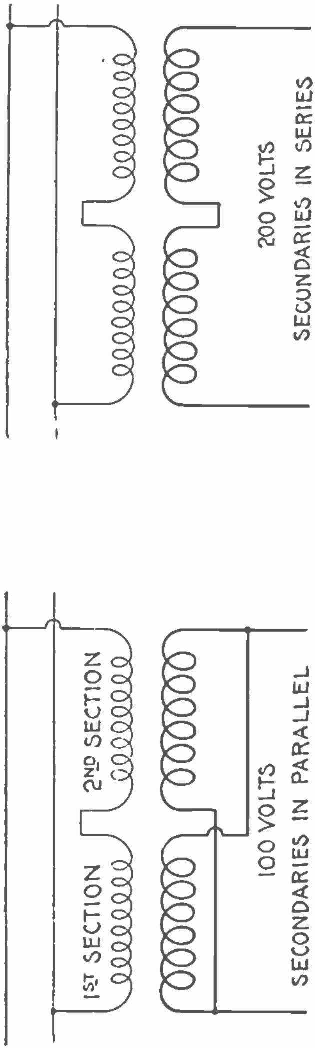
secondary terminals may each be considered exactly as the terminals of dynamos, with certain restrictions.

Ques. What are the two principal precautions which must be observed in combining transformer terminals?

Ans. It is primarily essential that the terminals have the same polarity at a given instant, and the transformers should have practically identical characteristics.

The latter condition is not absolutely essential but it is emphatically preferable. ***For example,*** if the turn ratio of the units be different, the secondary terminal voltages will not be the same. This means that at no load a circulating current will flow between the two units, and when loaded the transformers will not divide the load into proportion to their rated capacities.

In case the transformers have practically the same characteristics it is necessary as stated above, to make sure that the secondary terminals connected together have the same polarity



FIGS. 2,428 and 2,429.—Methods of altering the secondary connections of a transformer having two sections in the secondary to obtain a different voltage. Fig. 2,428 shows the two sections in parallel giving say 100 volts; fig. 2,429 shows the two sections in series giving 200 volts.

at a given instant; it is not necessary to find out definitely what the polarity is, merely that it is the same for both terminals. This can be easily done as shown in fig. 2,430.

Furthermore, if a transformer which has 2 per cent. regulation be connected in parallel, as indicated in fig. 2,431, with one which has 3 per cent. regulation, at no load the transformers will give exactly the same voltage at the secondary terminals, but at full load one will have a secondary pressure of, say, 98 volts, while the other has 97 volts. The result is that the transformer giving only 97 volts will be subject to a reverse pressure of one volt from its mate. This will not cause a current to flow backward through the secondary winding of the low voltage transformer, but it will disturb the phase relations and lower the power factor and efficiency of the combination. In such a case it is much better to work the secondary circuits of the two transformers separately.

Ques. Explain how secondary connections are made for different voltages.

Ans. If, for instance, the secondary pressure of a transformer having two sections be 100 volts with the terminals in parallel, as in fig. 2,428, then connecting them in series will give 200 volts at the free secondary terminals, as indicated in fig. 2,429.

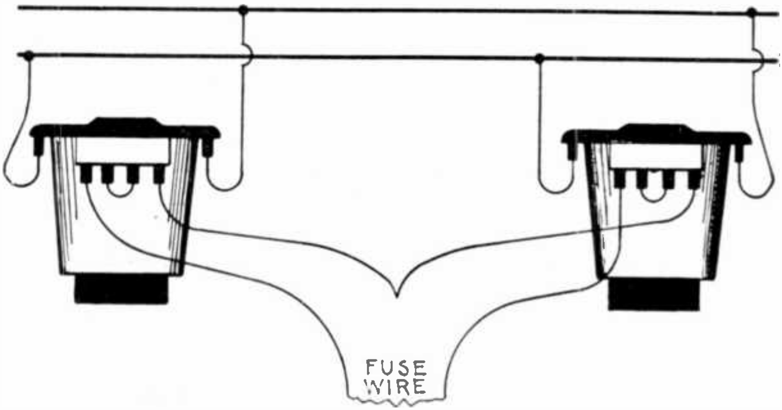


FIG. 2,430.—Method of comparing instantaneous polarities. Two of the terminals are connected as shown by a small strip of fuse wire, and then touching the other two terminals together. If the fuse blow, then the connections must be reversed; if it do not, then they may be made permanent.

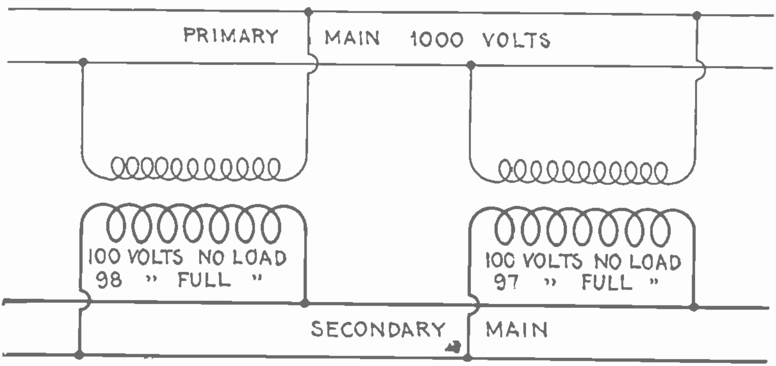


FIG. 2,431.—Diagram showing unlike single phase transformers in parallel.

Two Phase Connections.—In the case of two phase distribution each circuit may be treated as entirely independent of each other so far as the transformers are concerned. Two transformers are used, one being connected to one primary phase and supplying one secondary phase, the other being connected to the other primary phase and supplying the other

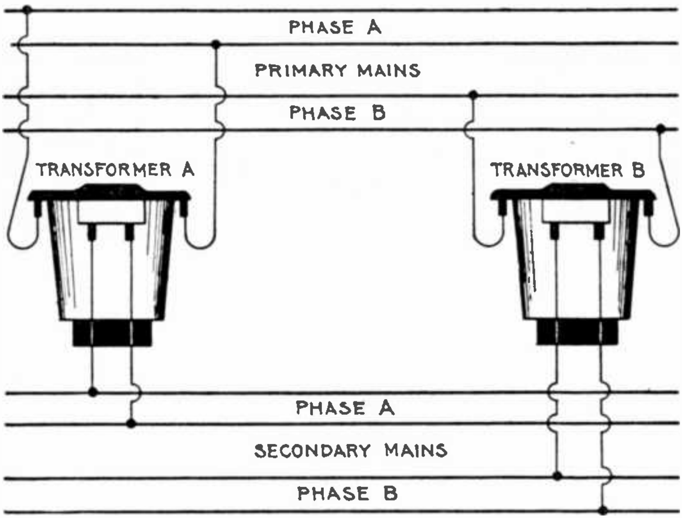


FIG. 2,432.—Two phase transformer connections. Two single phase transformers are used and connections made just as though each phase were an ordinary single phase system.

secondary phase as indicated in fig. 2,432, exactly as though each primary and secondary phase were an ordinary single phase system, independent of the other phase.

Ques. Is the above method usually employed?

Ans. No, the method shown in fig. 2,433 is generally used.

Three Phase Connections.—There is not so much freedom in making three phase transformer connections, as with single or two phase, because the three phases are inseparably interlinked. However, the system gives rise to several methods of transformer connection, which are known as:

1. Y or star;
2. Delta or mesh;
3. Y-delta;
4. Delta-Y.

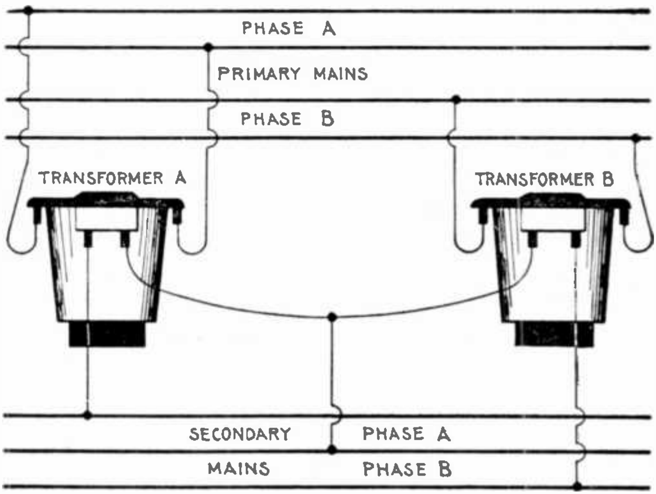
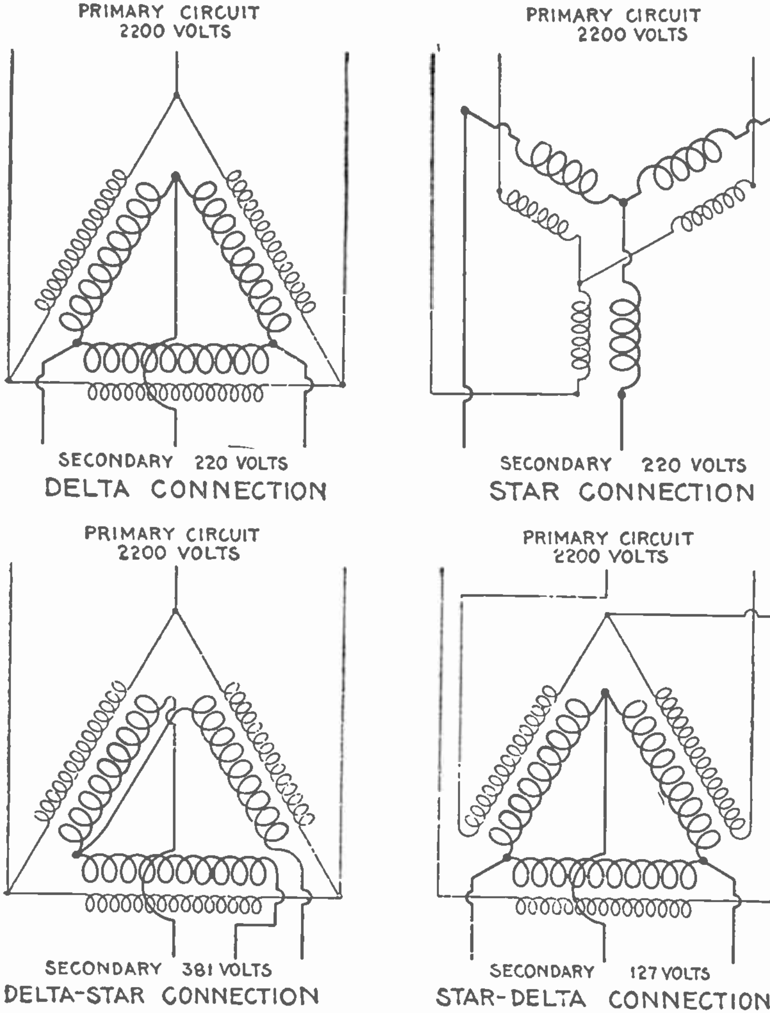


FIG. 2,433.—Two phase transformer connections, with secondaries arranged for three wire distribution, the primaries being independently connected to the two phases. In the three wire circuit, the middle or neutral wire is made about one-half larger than each of the two outer wires. In fig. 2,432 it makes no difference which secondary terminal of a transformer is connected to a given secondary wire, so long as no transformers are used in parallel. For example, referring to the diagram, the left hand secondary terminal of transformer, A, could just as well be connected to the lower wire of the secondary phase, A, and its right hand terminal connected to the upper wire, the only requirement being that the two pairs of mains shall not be "mixed"; that is, transformer, A, must not be connected with one secondary terminal to phase, A, and the other to phase, B. In the case shown by fig. 2,433, there is not quite so much freedom in making connections. One secondary terminal of each transformer must be connected to one of the outer wires and the other two terminals must be both connected to the larger middle wire of the secondary system. It makes no difference, however, which two secondary terminals are joined and connected to the middle wire so long as the other terminal of each transformer is connected to an outer wire of the secondary system.



FIGS. 2,434 to 2,437.—Three phase transformer connections. Fig. 2,434 ***delta*** connection; fig. 2,435 ***star*** connection; fig. 2,436 ***delta-star*** connection; fig. 2,437 ***star-delta*** connection.

Delta Connection.—In the delta connection both primaries and secondaries are connected in delta grouping, as in fig. 2,434.

Y Connection.—This method consists in connecting both the primaries and secondaries in star grouping, as in fig. 2,435.

Delta Y Connection.—In this method the primaries are connected in delta grouping and the secondaries in star grouping, as in fig. 2,436.

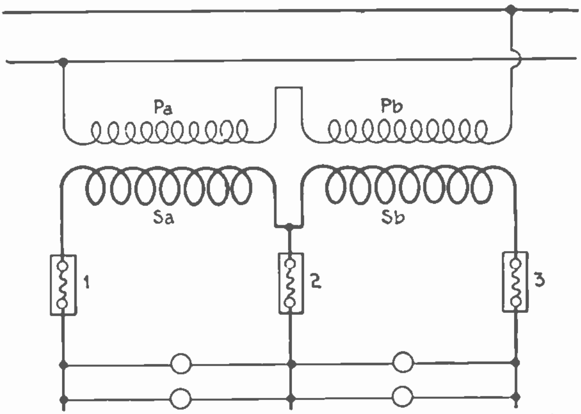


FIG. 2,438.—Three wire connections for transformer having two secondary sections on different legs of the core. If the secondary terminals be connected up to a three wire distribution, as here shown diagrammatically, it is advisable to make the fuse 2, in the middle wire, considerably smaller than necessary to pass the normal load in either side of the circuit, because, should the fuse 1, be blown, the secondary circuit through the section Sa, will be open, and the corresponding half of the primary winding Pa, will have a much higher impedance than the half of the primary winding Pb, the inductance of which is so nearly neutralized by the load on the secondary winding Sb. The result will be that the voltage of the primary section Pa, will be very much greater than that of the section Pb, and as the sections are in series the current must be the same through both halves of the winding; the drop or difference of pressure, therefore, between the terminals of Pa, will be much higher than that between the terminals of Pb, consequently, the secondary voltage of Sb, will be greatly lowered and the service impaired. As the primary winding Pa, is designed to take only one-half of the total voltage, the unbalancing referred to will subject it to a considerably higher pressure than the normal value; consequently, the magnetic density in that leg of the transformer core will be much higher than normal, and the transformer will heat disastrously. If the fuse 2, in the middle wire be made, say, one-half the capacity of each of the other fuses, this condition will be relieved by the blowing of this fuse, and as the lamps in the live circuit would not be anywhere near candle power if the circuit remained intact, the blowing of the middle fuse will not be any disadvantage to the user of the lamps. Some makers avoid the contingency just described by dividing each secondary coil into two sections and connecting a section on one leg in series with a section on the other leg of the core, so that current applied to either pair of the secondary terminals will circulate about both legs of the core.

Y Delta Connection.—This consists in connecting the primaries in star grouping, and the secondaries in delta grouping, as in fig. 2,437.

Ques. What advantage has the star connection over the delta connection?

Ans. Each star transformer is wound for only 58% of the line voltage. In high voltage transmission, this admits of much

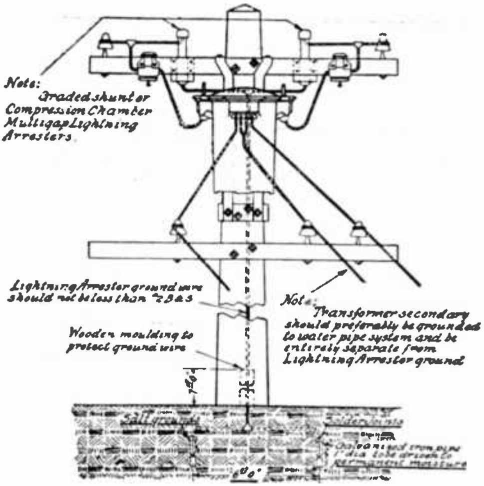


FIG. 2,439.—Installation of a transformer on pole; view showing method of attachment and disposition of the primary and secondary leads, cutouts, etc.

smaller transformers being built for high pressure than possible with the delta connection, because of less insulation.

Ques. What advantages are obtained with the delta connection?

Ans. When three transformers are delta connected, one may be removed and the two remaining units will carry 58% of the original three phase load.

The desire to guard against a shut down due to the disabling of one transformer has led to the extensive use of delta connection, especially for the secondaries or low pressure side.

It should be noted that if one transformer be disabled the efficiency of the other two will be greatly reduced.

Ques. How are transformers connected for four wire three phase distribution?

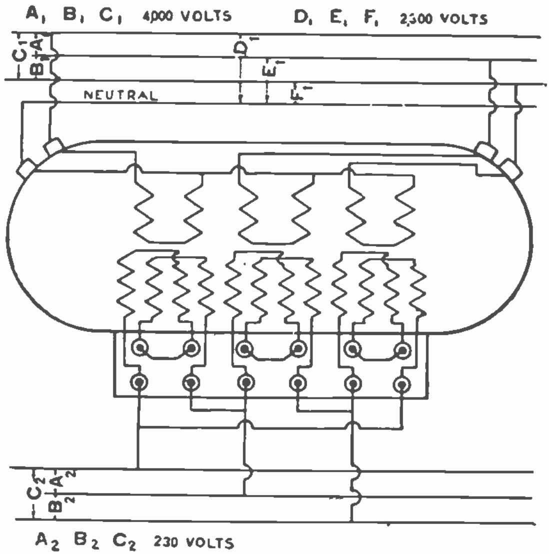


FIG. 2,440.—Pittsburgh connection diagram for three phase 4-wire star primary to three phase 4-wire star secondary.

Ans. When the secondaries of three transformers are star connected, a fourth wire may be run from the neutral point, thus obtaining the four wire system.

The voltage between any main wire and the neutral will be 57 per cent. of the voltage between any two main wires. For general distribution this system is desirable. requiring less copper and greater flexibility than other systems.

Three phase 200 volt motors may be supplied from the main wires and 115 volt lamps connected between each of the three main wires and the neutral; if the lamp load be very nearly balanced the current flowing in the neutral wire will be very small, as in the case of the ordinary three wire direct current system.

Ques. What kind of transformers are used for three phase current?

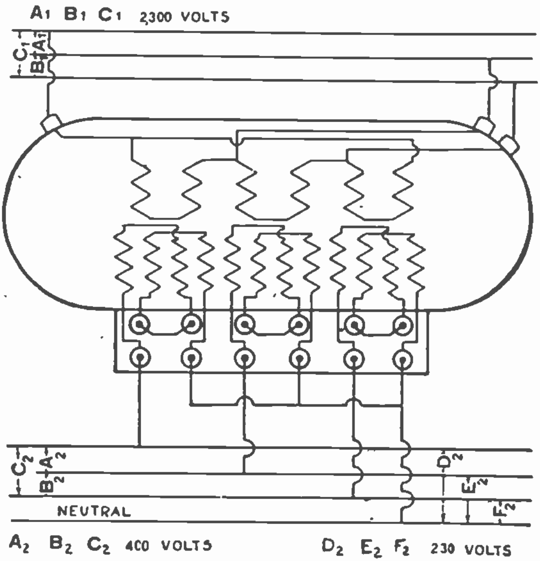


FIG. 2,441.—Pittsburgh connection diagram for three phase 3-wire closed delta primary to three phase 4-wire star secondary.

Ans. Either a three phase transformer, or a separate single phase transformer for each phase.

Ques. What points are to be considered in choosing between three phase and single phase transformers for three phase current transformation?

Ans. No specific rule can be given regarding the selection of single phase or three phase transformers since both designs are equally reliable; local conditions will generally determine which type is preferable.

The following general remarks may, however, be helpful:

Single phase transformers are preferable where only one transformer group is installed and where the expense of a spare transformer would not be warranted. In such installations the burn out of one phase of a three phase unit would cause considerable inconvenience for the reason that the whole transformer would have to be disconnected from the circuit before repairs could be made.

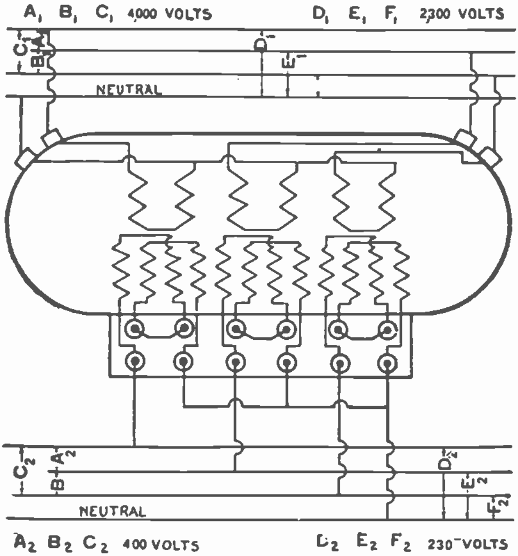
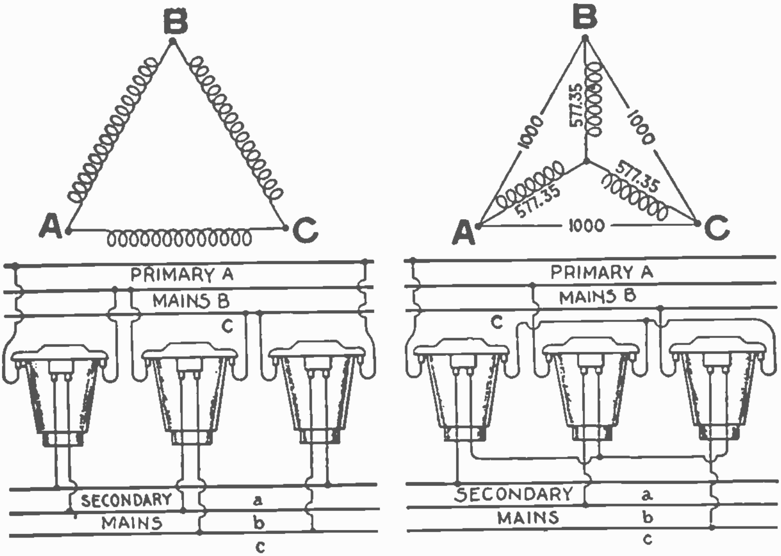


FIG. 2,442.—Pittsburgh connection diagram for three phase 4-wire star primary to three phase 4-wire star secondary.

If single phase transformers be used and connected in delta on both primary and secondary, the damaged transformer can be cut out with a minimum amount of trouble and the other two transformers can be operated at normal temperature open delta at 58 per cent. of the normal capacity of the group of three transformers, until the third unit can be replaced.

Open delta operation of any but small, low voltage transformers (whether single phase or three phase units) is not recommended except in an emergency due to the following considerations:



FIGS. 2,443 to 2,446.—Three phase delta, and star connections using three transformers. There are two ways of connecting up the primaries and secondaries, one known as the "delta" connection, and illustrated diagrammatically by fig. 2,443, and the other known as the "star" connection, and illustrated by fig. 2,445. In both diagrams the line wires are lettered, A, B and C. Fig. 2,444 shows the primaries and secondaries connected up delta fashion, corresponding to fig. 2,443, and fig. 2,446 shows them connected up star fashion, corresponding to fig. 2,445. In both of the latter sketches the secondary wires are lettered to correspond with the respective primary wires. When the primaries are connected up delta fashion, the voltage between the terminals of each primary winding is the same as the voltage between the corresponding two wires of the primary circuit, and the same is true of the secondary transformer terminals and circuit wires. The current, however, flowing through the transformer winding is less than the current in the line wire, for the reason that the current from any one line wire divides between the windings of two transformers. For example, in figs. 2,443 and 2,444, part of the current from the line wire, A, will flow from A, to B, through the left hand transformer, and part from A, to C, through the right hand transformer; if the current in the line wire A, be 100 amperes, the current in each transformer winding will be 57.735 amperes. When transformers are connected up star fashion, as in figs. 2,445 and 2,446, the current in each transformer winding is the same as that in the line wire to which it is connected, but the voltage between the terminals of each transformer winding is 57.735 per cent. of the voltage from wire to wire on the circuit. For example, if the primary voltage from A, to B, be 1,000 volts, the voltage at the terminals of the

1. The internal power factor of the bank being only 86.6%, the active units or coils can deliver only 86.6% of their rated *kva.*;

2. An open delta bank is somewhat more liable to damage under abnormal voltage disturbances than a closed delta bank;

Shell type. When necessary to operate a three phase shell type transformer open delta, due to a damaged winding, care should be taken to see that both primary and secondary windings of the damaged phase are not only disconnected but also short circuited upon themselves, otherwise greater damage may result. By short circuiting the windings the magnetic flux in that section of the core is neutralized.

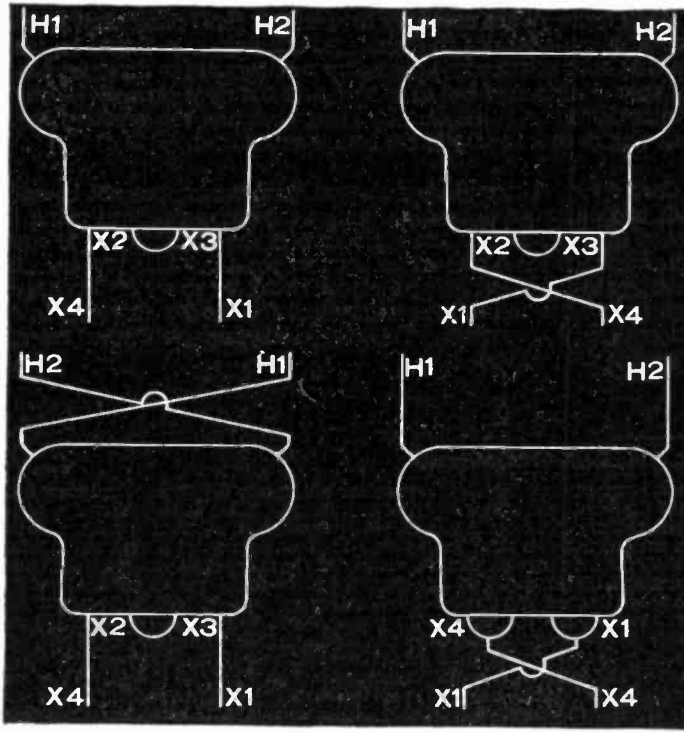
Core type. Three phase core type transformers can not be operated with two phases in open delta, unless the entire damaged phase be removed from the core or else every turn of the damaged coil is open circuited and the series connection between the other coils broken. This is necessary because the damaged phase is subject to very high voltages and high frequencies and unless sectionalized so that few turns are in series, serious damage may result. This is especially important when the voltage is greater than 44,000.

FIGS. 2,443 to 2,446.—***Text continued.***

left hand transformer (from A, to star point,) will be only 577.35 volts, and same is true of each of the other transformers if system be balanced. These statements apply, of course, to both primary and secondary windings, from which it will become evident that if the three transformers of a three phase circuit be connected up star fashion at the primaries, and delta fashion at the secondaries, the secondary voltage will be lower than if both sides be connected up star fashion. ***For example,*** if the transformers be wound for a ratio of 10 to 1, and be connected up with both primaries and secondaries alike, no matter whether it be delta fashion or star fashion, the secondary voltage will be one-tenth of the primary voltage; but if the primaries be connected up star fashion on a 1,000 volt circuit, and the secondaries be connected up delta fashion, the secondary voltage will be only 57.735 volts, instead of 100 volts. The explanation of the difference between the voltage per coil in a delta system and that in a star system is that in the former each winding is connected directly across from wire to wire; whereas in the star system, two windings are in series between each pair of line wires. The voltage of each winding is not reduced to one-half, however, because the pressures are out of phase with each other, being 120°, or one-third of a cycle, apart; consequently, instead of having 500 volts at the terminals of each coil in fig. 2,445 the voltage is 577.35. The same explanation applies to the current values in a delta system. The current phase between A and B, in fig. 2,443, is 120° removed from that in the winding between A and C; consequently, the sum of the two currents, in the wire, A, is 1.732 times the current in each wire; or, to state it the opposite way, the current in each winding is 57.735% of the current in the wire, A. It will be well for the reader to remember that in all cases pressures differing in phase when connected in series, combine according to the well-known law of the parallelogram of forces; currents differing in phase, and connected in parallel, combine according to the same law.

Where a large number of three phase transformers can be used, it is generally advisable to install three phase units, the following advantages being in their favor as compared with single phase units:

1. Require less floor space than three single phase units;
2. Weigh less than the single phase units;



FIGS. 2,447 to 2,450.—Pittsburgh polarity diagrams. In accordance with A.I.E.E., N.E.L.A. and E.P.C standards, Pittsburgh distribution transformers, single phase, 200 *kva*. and smaller, with high voltage, rating 7,500 volts and lower, are additive polarity. Heretofore, Pittsburgh distribution transformers were subtractive polarity. This change has been made to conform to present standards. To change polarity, cross either high tension or low tension leads as here shown. Fig. 2,447, additive polarity; fig. 2,448, polarity changed from additive to subtractive by crossing the low tension leads; fig. 2,449, polarity changed from additive to subtractive, by crossing the high tension leads; fig. 2450, polarity changed from additive to subtractive by crossing the low tension leads; low tension in parallel.

3. Simpler connections, as only three primary and three secondary leads are generally brought out;

4. Transformer presents a symmetrical and compact appearance.

Ques. What is the character of the construction of three phase transformers?

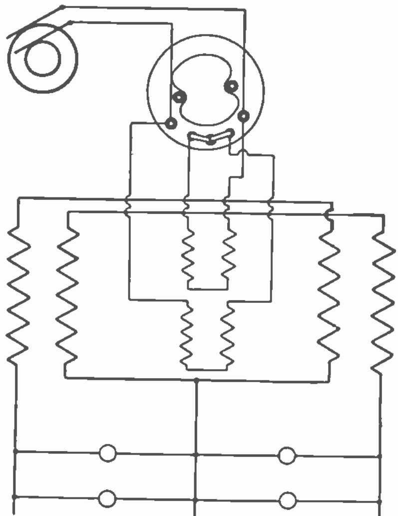


FIG. 2,451.—Diagram showing three wire secondary connections General Electric (type H) transformer. As will be seen, the method adopted consists of distributing equally, on each side of the primary coil, both halves of the secondary winding, so that each secondary throughout its length is closely adjacent to the entire primary winding. In order to insure the exact equality of resistance and reactance in the two secondary windings necessary to obtain perfect regulation of the two halves, the inside portion of the secondary winding on one side of the primary coil is connected in series with the outside portion of that on the other side. As a result, the drop of voltage in either side of the secondary under any ordinary conditions of unbalanced load, does not exceed the listed regulation drop. This particular arrangement is used because it is the simplest and best method for this construction.

Ans. The three phase transformer is practically similar to that of the single phase, except that somewhat heavier and larger parts are required for the core structure.

Transformer Operation with Grounded Secondary.—The operation of a transformer with a grounded secondary has been approved by the American Institute of Electrical Engineers, and by the National Board of Fire Underwriters.

This method of operation effectually prevents a high voltage occurring upon the low tension wires in case of a breakdown or other electrical connections occurring between the primary and secondary windings.

In case of a breakdown without the secondary grounded, any one touching a part of the low tension system, such as a lamp socket, might receive

COMPARISON OF AIR BLAST, WATER COOLED, AND OIL COOLED TRANSFORMERS

Air blast type	Water cooled type	Oil cooled type
1. COST		
A. First cost Necessarily more expensive than the water cooled type of similar rating.	Least expensive of all types.	Necessarily more expensive than the air blast and water cooled type of similar rating.
B. The installation is extremely simple. Moisture that may have collected on the surfaces during transportation or storage should be thoroughly dried out.	Being heavier than the air blast type, these transformers, as a rule, require heavier apparatus for installing. Both transformer and tank should be thoroughly dried out before being filled with oil. The oil is usually supplied in 50 gal. hermetically sealed steel barrels to minimize possibility of absorbing moisture during transportation.	The transformer is usually shipped filled with oil in order to prevent the windings absorbing moisture during shipment, also to conserve space. Otherwise the oil is supplied in hermetically sealed steel drums. Water cooling pipes are in most cases brought out to the side of the tank.

C. Auxiliary apparatus A duct, or chamber, of considerable size is required under the transformers in order to conduct the cooling air to them. A blower outfit for supplying air is required.	In most cases, cooling water may be obtained with sufficient natural head. However, there are frequent cases in which it can be obtained only by the use of pumps. A system of piping for the cooling water and oil drainage is required, the cost of which depends, of course, on the station layout.	Do not require cooling water or blower.
D. Maintenance An occasional cleaning, for which a supply of compressed air at about 20 lb. pressure is recommended. The blower outfit requires no more care than any other similar apparatus.	A water pumping outfit would possibly require a trifle more attention than a blower outfit in which there are no valves or piping.	No air or water circulation to demand attention.

2. FLOOR SPACE

Always requires space for cooling apparatus.	Extra space only required when auxiliary pumping apparatus is necessary.	Only require space for the transformer as no extra apparatus is necessary.

3. LOCATION

As the transformers are open at the top they should not be located where there is much dust or dirt nor where water from any source is liable to fall on them. The blower should be so situated as to obtain clean dry air of a temperature not greater than 77° Fahr.	Transformers are completely enclosed but location should be such that no water will fall on leads or bushings. Location of auxiliary apparatus will depend on the station layout.	Transformers are completely enclosed but location should be such that no water will fall on leads or bushings. The building should be well ventilated. There is no auxiliary apparatus.

the full high pressure voltage. With the low tension grounded, the fuse in the high tension circuit will blow and the fault be discovered upon replacing it.

4. GENERAL APPEARANCE

Terminal leads may be located in the base and the air chamber may be used for conducting and distributing the connecting wiring. The absence of overhead wiring aids in simplifying the appearance of the station.	Leads are brought out of the top of the transformers. Water cooling pipes are connected at the top in most cases.	Leads are brought out of the top of the transformers.

5. OPERATION

Equal reliability in all three types.

While full load efficiencies are practically equal in the three designs, it is necessary to change the proportion of iron and copper losses somewhat as the copper loss of the air blast transformer is a smaller part of its total loss than of the water cooled and oil cooled types. As a result, the regulation of the air blast transformer is a trifle better.

6. GENERAL

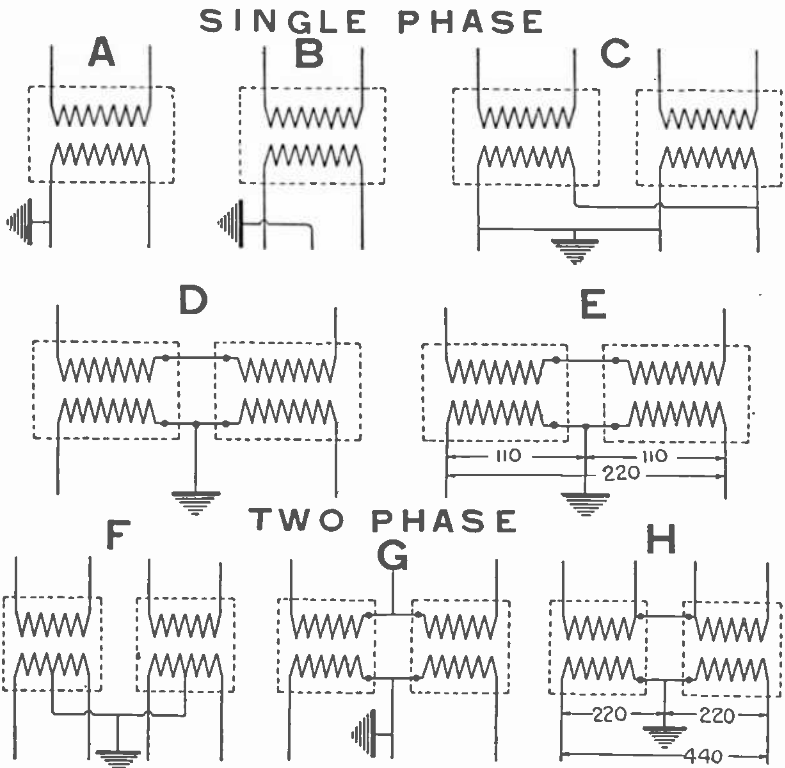
The above information regarding selection of type is not applicable to air blast transformers for circuits materially in excess of 33,000 volts.

On account of the great thickness of the solid insulation needed and the consequent difficulty in radiating heat from the copper, it is impracticable to design the air blast type for more than this voltage. The oil immersed designs are therefore recommended for transformers above 33,000 volts.

Both oil cooled and water cooled types are available for all voltages, being restricted in this respect only by the limitations of transmission facilities.

NOTE.—Except for air blast units, no special foundations are necessary for any type of transformer other than a good even floor, having sufficient strength to support the weight.

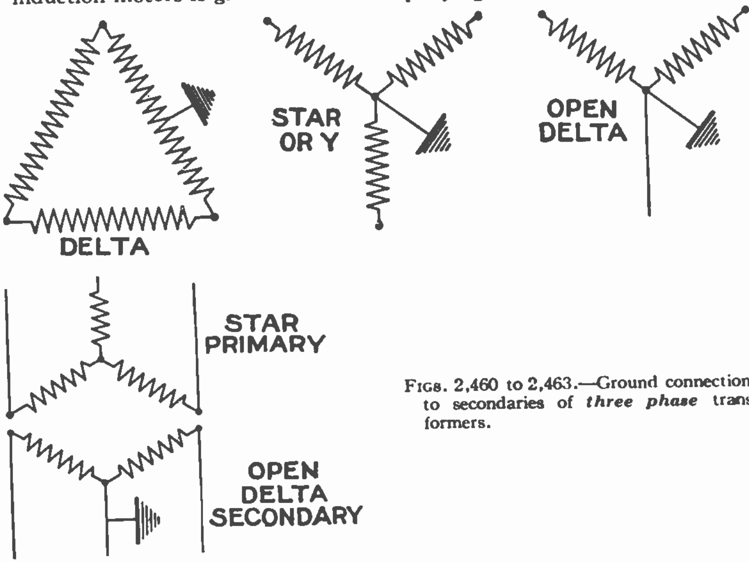
Transformer Capacity for Motors.—The voltage regulation of a well designed transformer is within 3 per cent. of its rated voltage on a non-inductive load such as incandescent lamps, but when motors are connected to the circuit their self-induction



FIGS. 2,452 to 2,459.—Ground connections to secondaries of *single phase* transformers. A, two wire; B, three wire; C, two separate 110 volt transformers in parallel, the secondary ground is attached to either wire; D, two windings, two wire; E, two windings, three wire; F, four wire; G, three wire; H, three wire with four wire primary.

causes a loss of 5 per cent. or more, and if the load be fluctuating, it is better to use independent transformers for the motor, which will prevent considerable fluctuations in the incandescent lamps.

Arc lamps do not show slight voltage changes as much as incandescent lamps. The proper rating of transformers for two phase and three phase induction motors is given in the accompanying table.



Figs. 2,460 to 2,463.—Ground connections to secondaries of *three phase* transformers.

A three phase induction motor may be operated from three single phase transformers or one three phase transformer. While the one three phase transformer greatly reduces the space and simplifies the wiring, the use of three single phase transformers is more flexible and, in case one transformer burn out, the connection can be readily changed so that two transformers will operate the motor at reduced load until the burned out transformer is replaced or repaired.

It is well to allow one kilowatt per horse power of the motor in selecting the size for the transformers, excepting in the small sizes when a little larger kilowatt rating is found to be the most desirable.

Transformers for Two and Three Phase Motors.

Delivered voltage of circuit	Single phase transformer voltages			
	110 volt motor		220 volt motor	
	Primary	Secondary	Primary	Secondary
1,100 2,200	1,100 2,200	122 122	1,100 2,200	244 244

Very small transformers should not be used, even when the motor is large compared to the work it has to do, as the heavy starting current may burn them out.

The following tables give the proper sizes of transformer for three types of induction motor and the approximate current taken by three phase induction motors at 220 volts.

Capacities of Transformers for Induction Motors

Size of motor horse power	Kilowatts per transformer		
	Two single phase transformers	Three single phase Transformers	One three phase transformer
1	0.6	0.6	
2	1.5	1.0	2.0
3	2.0	1.5	3.0
5	3.0	2.0	5.0
7	4.0	3.0	7.5
10	5.0	4.0	10.0
15	7.5	5.0	15.0
20	10.0	7.5	20.0
30	15.0	10.0	30.0
50	25.0	15.0	50.0
75	40.0	25.0	75.0
100	50.0	30.0	100.0

Current Taken by Three Phase Induction Motors at 220 Volts

Horse power of motor	Approximate full load current	Horse power of motor	Approximate full load current
1	3.2	20	50.
2	6.0	30	75.
3	9.0	50	125.
5	14.0	75	185.
10	27.0	100	250.
15	40.0	150	370.

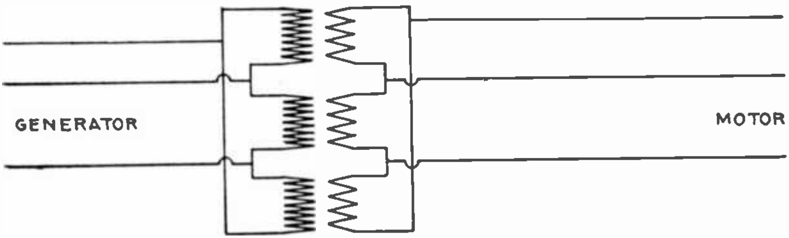


FIG. 2,464.—Three phase motor transformer connections; the so-called delta connected transformers.

Transformer Connections for Motors.—Fig. 2,464 shows the connection of a three phase so called delta connected transformer with the three primaries connected to the lines leading from the alternator and the three secondaries leading to the motor.

The connections for a three phase motor using two transformers is shown in fig. 2,465 and is identical with the previous arrangement except that one transformer is left out and the other two made correspondingly larger.

The copper required in any three wire three phase circuit for a given power and loss is 75 per cent. of that necessary with the two wire single phase or four wire two phase system having the same voltage between lines.

The connections of three transformers for a low tension system of distribution by the four wire three phase system are shown in fig. 2,466. The three transformers have their primaries joined in delta connection and the secondaries in "Y" connection. The three upper lines of the secondary are the three main three phase lines, and the lowest line is the common neutral.

The voltage across the main conductors is 200 volts, while that between either of them and the neutral is 115 volts; 200 volt motors should be joined to the mains while 115 volt lamps are connected between the mains and neutral. The arrangement is similar to the Edison three wire system and the neutral carries current only when the lamp load is unbalanced.

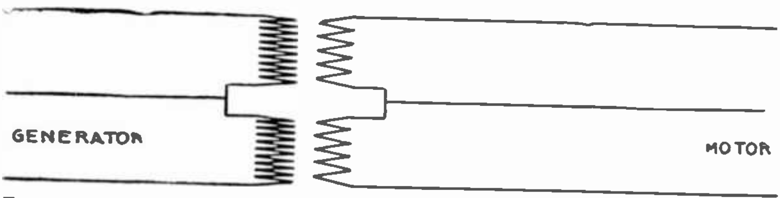


Fig. 2,465.—Three phase motor connections using two transformers.

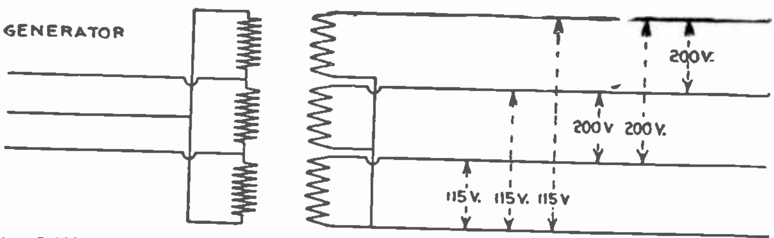


Fig. 2,466.—Delta-star connection of three transformers for low pressure, three phase, four wire system.

The voltage between the mains should be used in calculating the size of wires, and the size of the neutral wire should be made in proportion to each of the main conductors as the lighting load is to the total load.

When lights only are used the neutral should be the same as the main conductors. The copper required in such a system for a given power and loss is about 33.3 per cent. as compared with a two wire single phase system or a four wire two phase system using the same voltage.

Monocyclic Motor System.—Motors on the monocyclic system are operated from two transformers connected as shown in fig. 2,467. In the monocyclic system the single phase current is used to supply the lighting load and two wires only are necessary, but if a self-starting induction motor be required, a third or *teaser wire* is brought to the motor and two transformers used.

The teaser wire supplies the quarter phase current required to start the motor, which afterwards runs as a single phase synchronous motor and little or no current flows through the teaser circuit as long as the motor keeps in synchronism; in case it fall behind, the teaser current tends to bring it up to speed instead of the motor stopping, as would be the case of a single phase motor.

The voltage of the transformers should be tested by means of a volt meter or two incandescent lamps joined in series, before starting up the

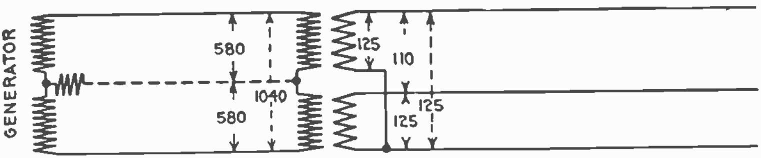


FIG. 2,467.—Diagram of transformer connections for motors on the monocyclic system.

motor, to see if the proper transformer connections have been made and to prevent an excessive flow of current.

If one of the transformers be reversed, the voltage will be almost doubled; in fact, it is a good plan to check up all the transformer connections with the volt meter or lamps which will often save a burn out.

Transformation of Phases.—In alternating current circuits it is frequently desirable to change from one number of phases to another. For instance, in the case of a converter, it is less expensive and more efficient to use one built for six phases than for either two or three phases.

The numerous conditions met with necessitate various phase transformations, as:

1. Three phase to single phase;
2. Three phase to two phase;
3. Two phase to six phase;
4. Three phase to six phase.

These transformations are accomplished by the numerous arrangements and combinations of the transformers.

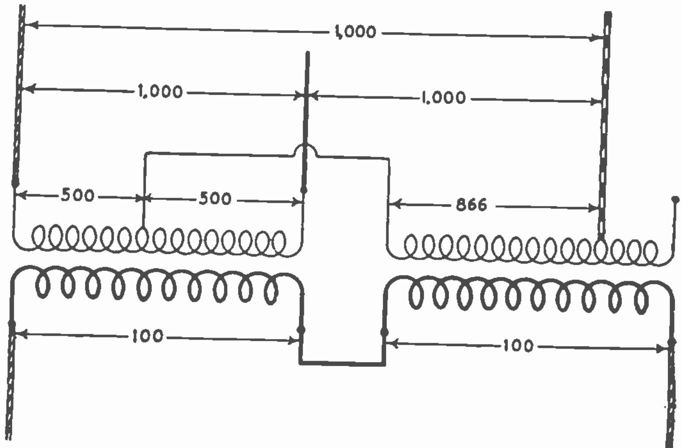


FIG. 2,468.—Three phase to one phase transformation with two transformers. The diagram shows the necessary connections and the relative pressures obtained.

Three Phase to One Phase.—This transformation may be accomplished by the use of two transformers connected as in fig. 2,468 in which one end of one primary winding is connected to the middle of the other primary winding and the second end of the first primary winding at a point giving 86.6 per cent of that winding as shown. The two secondary windings are joined in series.

Three Phase to Two Phase.—The three phase system is universally used for long distance transmission, because it requires less copper than either the single or two phase systems. For distribution, however, the two phase system presents certain advantages, thus, it becomes desirable at the distribution centers to change from three phase to two phase. This may be done in several ways.

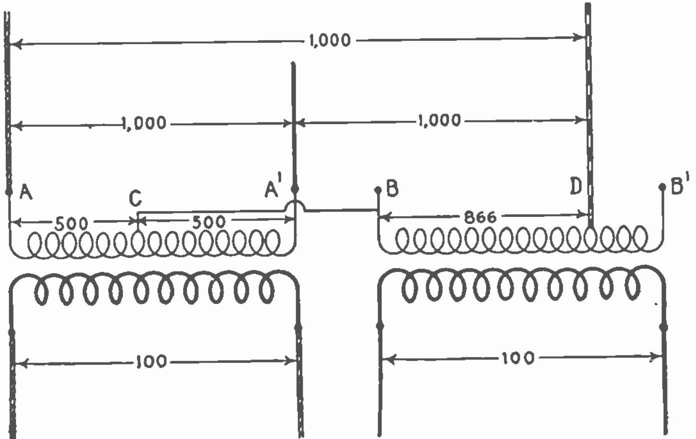


FIG. 2,469.—The Scott connection for transforming from three phase to two phase. In this method one of the primary wires B, of the .866 ratio transformer is connected to the middle of the other primary as at C, the ends of which are connected to two of the three phase wires. The other phase wire is connected at D, the point giving the .866 ratio. The secondary wires are connected as shown.

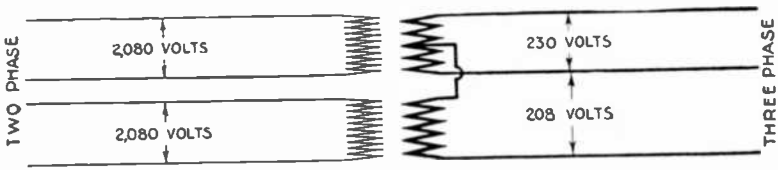


FIG. 2,470.—Diagram showing a method of operating a three phase motor on a two phase circuit, using a transformer having a tap made in the middle of the secondary winding, so as to get the necessary additional phase. While this does not give a true balanced three phase secondary, it is close enough for motor work. In the above arrangement, the main transformer supplies 54 per cent. of the current and the other with the split winding 46 per cent.

Ques. Describe the Scott connection.

Ans. Two transformers are used, one having a 10:1 ratio and the other, a $\frac{1}{2}\sqrt{3}:1$, that is, an .866 : 1 ratio. The connections are arranged as in fig. 2,469.

This may be accomplished by using standard transformers having the ratios 10: 1, and 9 : 1.

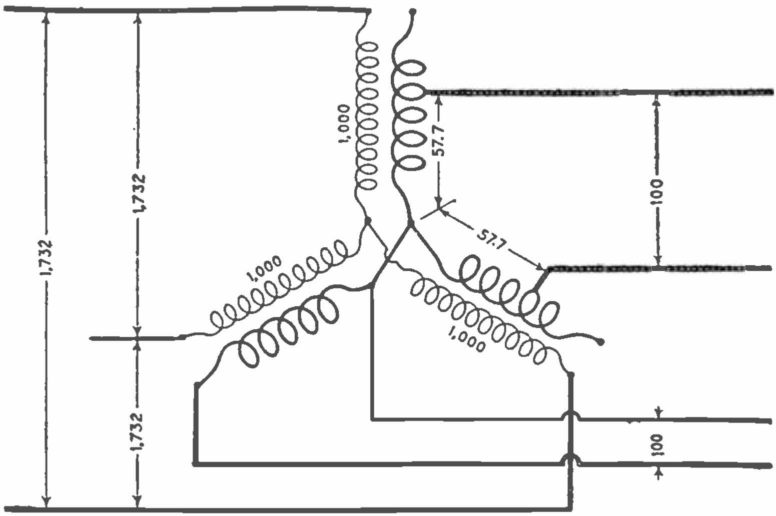


FIG. 2,471.—Three phase to two phase transformation with three star connected transformers. Two of the secondary windings are tapped at points corresponding to 57.7% of full voltage; these two windings are connected in series to form one secondary phase of voltage equal to that obtained by the other full secondary winding.

Ques. What names are given to the two transformers?

Ans. The one having the 10 : 1 ratio is called the **main** transformer, and the other with the 8.66 : 1 ratio, the **teaser** transformer.

In construction, the transformers may be made exactly alike so that either may be used as main or teaser.

In order that the connections may be properly and conveniently made, the primary windings should be provided with 50% and 86.6% taps.

Ques. Describe another way of transforming from three to two phases.

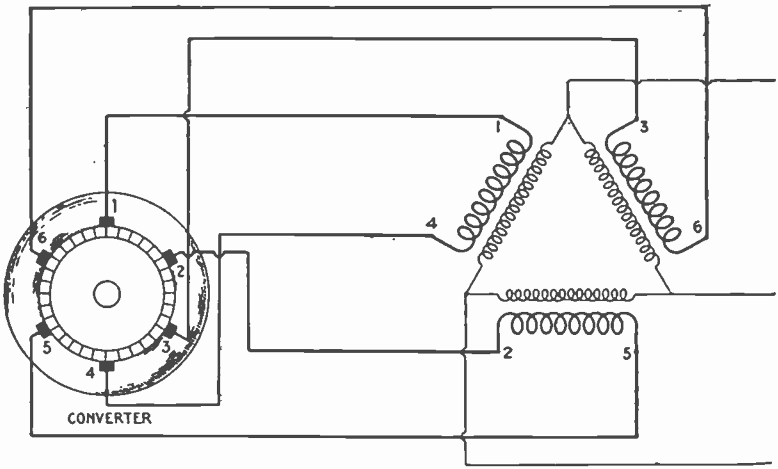


FIG. 2,472.—Diagram of ***diametrical connection, three phase to six phase. It is obtained by bringing both ends of each secondary winding to opposite points on the rotary converter winding,*** utilizing the converter winding to give the six phases. This Transformation of phases may also be obtained with transformers having two secondary windings.

Ans. The transformation may be made by three star connected transformers, proportioning the windings as in fig. 2,471, from which it will be seen that two of the secondary windings are tapped at points corresponding to 57.7 per cent. of full voltage. This method, however, is very seldom used.

Three Phase to Six Phase.—This transformation is usually made for use with rotary converters and may be accomplished in several ways. As these methods have been illustrated in the chapter on Converters, it is unnecessary to again discuss them here. Fig. 2,472, shows the *diametrical* connection for transforming three phase to six phase.

TEST QUESTIONS

1. *How are single phase connections made?*
2. *Give directions for paralleling transformers.*
3. *What is the method of comparing instantaneous polarities?*
4. *Draw a sketch showing two phase transformer connections.*
5. *Give four methods of three phase connections.*
6. *What is the difference between the star and delta connections?*
7. *What advantage has the star connection over the delta connection?*
8. *What advantages are obtained with the delta connection?*
9. *How are transformers connected for four wire three phase distribution?*
10. *What kind of transformers are used for three phase current?*
11. *What points are to be considered in choosing between three phase and single phase transformers for three phase current transformation?*
12. *What is the character of the construction of three phase transformers?*

13. *Should a transformer be operated with a grounded secondary?*
14. *Give a comparison of air blast, water cooled, and oil cooled transformers.*
15. *What may be said about transformer capacity for motors?*
16. *Draw some diagrams showing transjormer connections for motors.*
17. *What is a monocyclic motor system?*
18. *In what ways may transformation of phases be made?*
19. *Describe the Scott connection.*
20. *What names are given to the two transformers used in the Scott connection?*

CHAPTER 54

Alternating Current Motors

(Classification)

The almost universal adoption of the alternating current system of distribution of electrical energy for light and power, and the many inherent advantages of the alternating current motor, have created the wide field of application now covered by this type of apparatus.

As many central stations furnish only alternating current, it has become necessary for motor manufacturers to perfect types of alternating current motor suitable for all classes of industrial drive and which are adapted for use on the kinds of alternating circuit employed. This has naturally resulted in a multiplicity of types and a classification, to be comprehensive, must, as in the case of alternators, divide the motors into groups as regarded from several points of view. Accordingly, alternating current motors may be classified:

1. With respect to their principle of operation, as

   a. SYNCHRONOUS MOTORS;
      1. Plain
      2. Super—

   b. ASYNCHRONOUS MOTORS;

      1. Induction motors;
      - squirrel cage { single; double;
      - internal resistance;
      - external resistance (slip ring);
      - single (split) phase.

- **2. Commutator motors**
  - *series*
    - single phase
    - universal
  - *compensated*
    - conductively
    - inductively
  - *shunt*
    - simple
    - compensated
  - *repulsion*
    - straight
    - compensated
  - *repulsion start induction*
    - brush lifting
    - short circuiting
  - *Repulsion induction*
- **3. Induction synchronous.**

2. With respect to the current, as
   - *a*. *Single phase*;
   - *b*. *Polyphase*.

3. With respect to speed, as
   - *a*. Constant speed;
   - *b*. Variable speed;
   - *c*. Adjustable speed.

4. With respect to structural features, as
   - *a*. Enclosed;
   - *b*. Semi-enclosed;
   - *c*. Open;
   - *d*. Pipe ventilated;
   - *e*. Back geared;
   - *f*. Skeleton frame;
   - *g*. Riveted frame;
   - *h*. Ventilated; etc.

Of the above divisions and sub-divisions some are self-defining and need little or no explanation; the others, however, will be considered in detail. with explanations of the principles of operation and construction.

CHAPTER 55

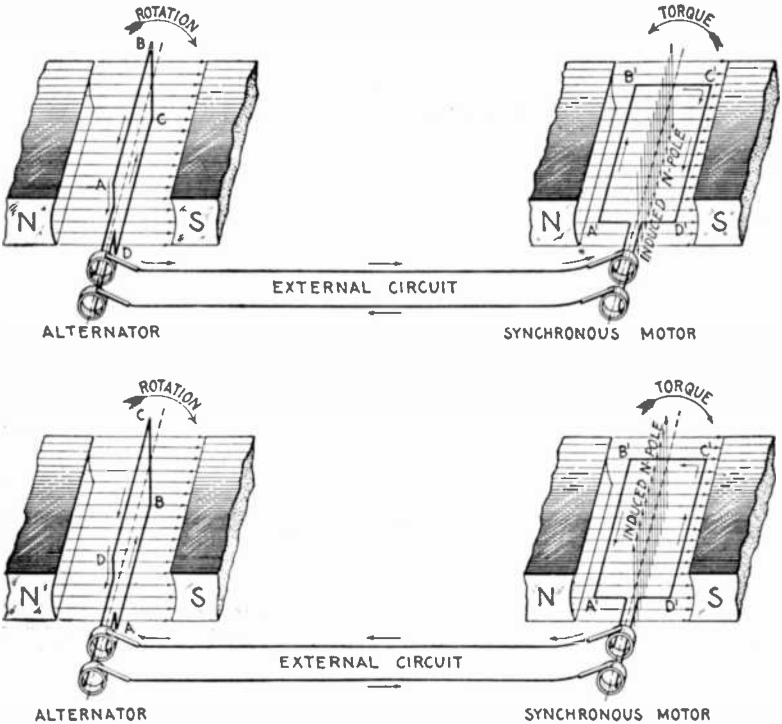
Synchronous Motors

The term "synchronous" means *in unison*, that is, *in step*. A so called synchronous motor, then, as generally defined, *is one which rotates in unison or in step with the phase of the alternating current which operates it.*

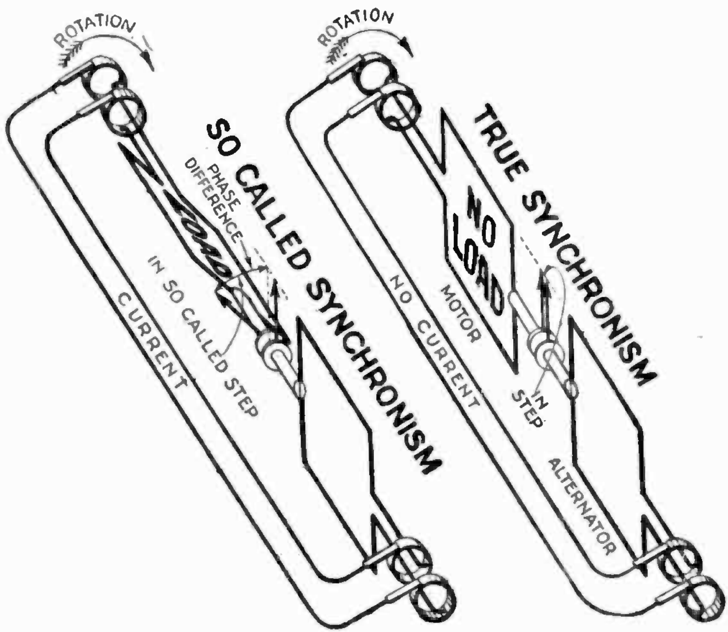
Fig. 2,473.—Musical definition of the term ***synchronous***. ***In an orchestra***, sometimes the 1st and 2nd violins play *in unison*, that is, *the same notes at the same time*. ***Similarly***, a synchronous motor (like the 2nd violins) operates (plays) in unison with the alternator (1st violins), that is, *similar inductors cut similar lines of force at the same time*; ***in other words***, a synchronous motor keeps in phase with the alternator which drives it. The speed of the motor is therefore fixed by the frequency of the supply. ***It should be noted*** that this is the ideal case of no load. If a load be put upon the motor it will cause a phase difference between the two machines, sufficient to balance the load as indicated in figs. 2,480 to 2,483.

Strictly speaking, however, it should be noted that this condition of operation is only approximately realized, as will be later shown.

Synchronous motors have been on the market and in use for many years, but not until recently, when power companies discovered their systems overloaded with wattless magnetizing current, has the synchronous motor been seriously considered for many of the classes of service



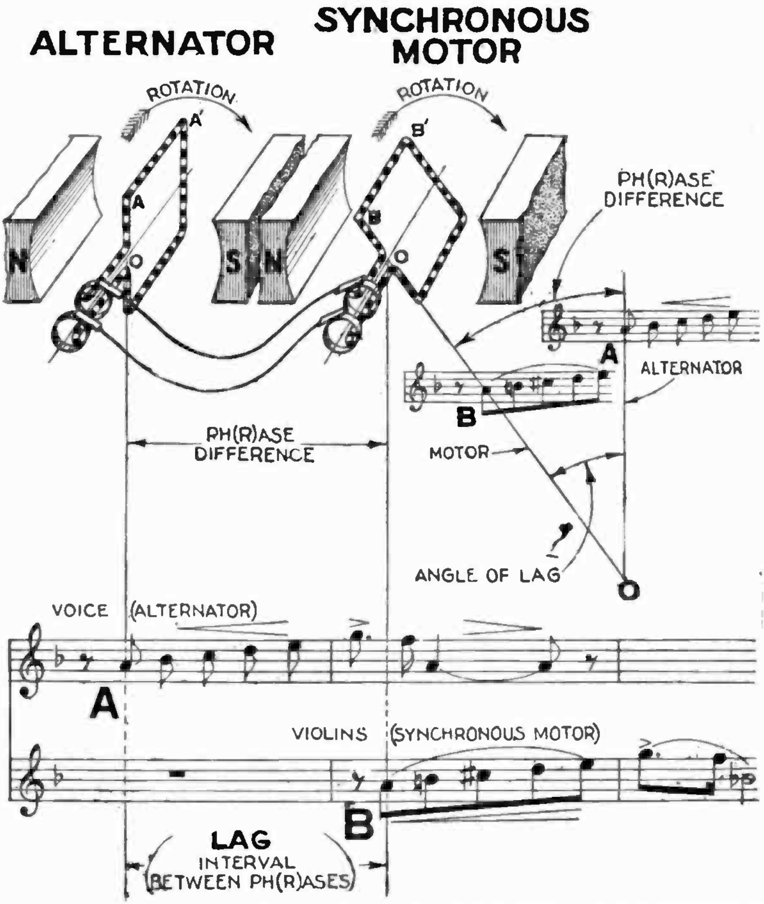
FIGS. 2,474 to 2,477.—Synchronous motor principles: I. *A single phase synchronous motor is not self-starting.* The figures show an elementary alternator and an elementary synchronous motor, the construction of all being identical as shown. If the alternator be started, during the first half of a revolution, beginning at the initial position ABCD, fig. 2,474, current will flow in the direction indicated by the arrows, passing through the external circuit and armature of the motor. fig. 2,475, inducing magnetic poles in the latter as shown by the vertical arrows. These poles are attracted by unlike poles of the field magnets, which tend to turn the motor armature in a counter-clockwise direction. Now, *before the torque thus set up has time to overcome the inertia of the motor armature and cause it to rotate, the alternator armature has completed the half revolution*, and beginning the second half of the revolution, as in fig. 2,476, *the current is reversed* and consequently *the induced magnetic poles in the motor armature are reversed also.* This tends to rotate the armature in the reverse direction, as in fig. 2,477. *These reversals of current occur with such frequency that the force does not act long enough in either direction to overcome the inertia of the armature; consequently it remains at rest*, or to be exact, *it vibrates.* Hence, a single phase synchronous motor must be started by some external force and brought



FIGS. 2,478 and 2,.479—True, and so called synchronism. A so called synchronous motor is supposed to run in synchronism with the alternator which drives it, but as a matter of fact it does not. Fig. 2.479 shows the conditions for synchronous operation. Here the motor has no load—neither external load nor internal load such as friction. Under these conditions the pressures induced in the alternator and motor would be equal and opposite and accordingly no current will flow. This is impossible in practice as there is always a load on the motor due to friction. ***What actually happens*** is this: Assuming the machine to be running in true synchronism as in fig. 2,479, when a load is applied, the motor unable to supply the torque demand, *slows down*. Before the armature has settled back more than a few degrees from its synchronous position, the change in the phase causes a decrease in the motor pressure, giving an excess of forward pressure to let sufficient current flow in the motor armature to balance the load. The motor at this instant has increased its speed and is running at the same speed as the alternator, the phase difference being indicated in fig. 2,478.

FIGS. 2,474 to 2,477.—*Text continued.*

up to a speed that gives the same frequency as the alternator before it will operate. A single phase synchronous motor, then, is not self-starting, which is one of its disadvantages. The reason it will operate after being speeded up to synchronism with the alternator and then connected in the circuit is explained in figs. 2,487 to 2,490.



FIGS. 2,480 to 2,483.—Musical analogy illustrating phase difference between alternator and synchronous motor due to load on motor. Analyzing the music, which is a passage from Scene 2, Act 3 of ***Bruno Oscar Klein's*** opera "***Kenilworth,***" even those having little or no musical knowledge will clearly see that a vocal phrase **A**, is followed at a time interval (*ph(r)ase difference*) by a similar phrase, **B**, in the orchestral accompaniment. ***Similarly***, if **AA'**, be an instantaneous position of one of the alternator inductors, the corresponding inductor in the motor will lag behind **AA'**, at some position as **BB'**, to balance the load. Fig. 2,482, shows the angle of lag **AOB**. The greater the load, the greater the angle of lag; the reason for this is explained in figs. 2,493 and 2,494.

for which it is eminently desirable. This has resulted in a largely increased demand for synchronous motors in the past few years and has led to the building of many different sizes for various applications, and as time goes on, the application of synchronous motors will become much more general than it has been in the past.

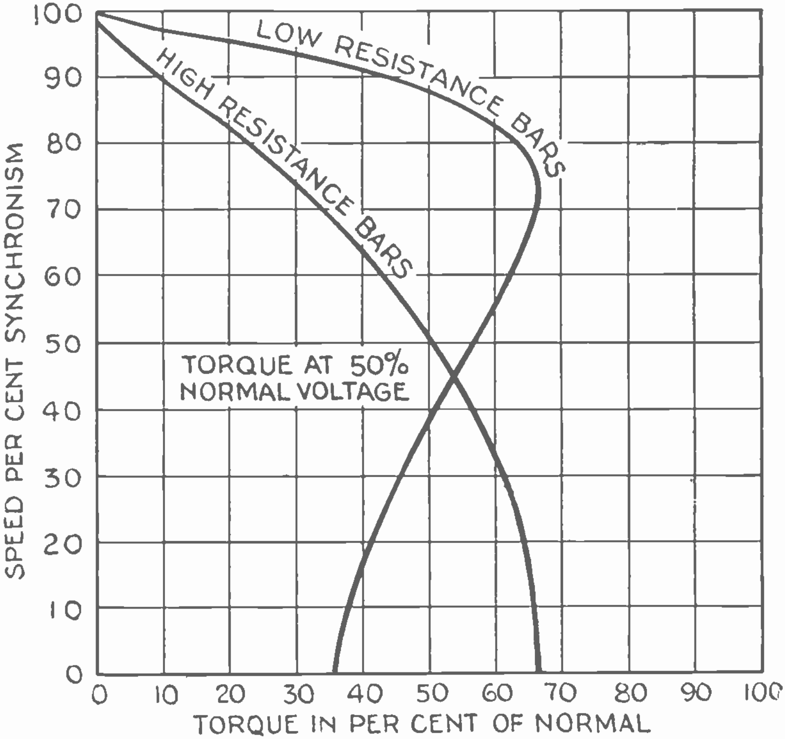


FIG. 2,484.—Starting torque curves for a synchronous motor with *low and high resistance squirrel cages* on the armature. ***In order that*** a synchronous motor may pull into step, it is necessary to accelerate it until synchronous speed is quite closely approached. The nearer this approach, the more powerful is the synchronizing action. The slip of an induction motor depends upon the load and also upon the resistance in the cage winding. If a high cage resistance be used in order to provide a high starting torque, it is quite possible that the slip will be so great that sufficient synchronizing action cannot be developed to pull the motor into step. The curves show the difference in effect of high resistance brass bars and low resistance copper bars.

The increasing demand has led to a careful investigation of design so that the modern synchronous motor is a machine of special construction and not merely an alternator with a squirrel cage winding added to the rotor poles. They are now built with very satisfactory "starting and pull in torque characteristics" which also accounts for the increasing demand in recent years. Even in installations where the starting characteristics are such that a synchronous motor would not start, the difficulty is overcome by the use of a magnetic clutch in conjunction with the synchronous motor.

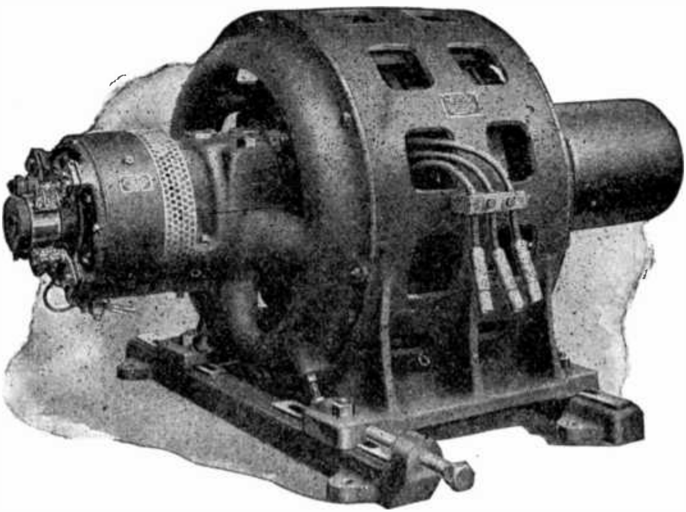


FIG. 2,485.—Allis Chalmers synchronous motor with direct connected exciter. This type machine is made only in the smaller sizes and is of self-contained or bracket bearing construction for more or less high speed work. The feet of the stator yoke rest directly on the base or slide rails, a base being provided where three bearing belted parts are required

The motor is brought up to speed and thrown into synchronism after which it is connected to the driven load by means of the magnetic clutch.

The uniformly high efficiency at fractional loads and at all speeds, constant speed under varying loads, the ability to operate at unity power factor regardless of the power factor of the line together with the power factor corrective effect that may be obtained by increasing the excitation are prime reasons for this increasing demand.

Any single or polyphase alternator will operate as a synchronous motor when supplied with current at the same pressure frequency and wave shape as it produces as an alternator, the essential condition, in the case of a single phase machine, being that it be speeded up to so called synchronism before being put in the circuit.

In construction, synchronous motors are almost identical with the corresponding alternator, and consist essentially of two elements:

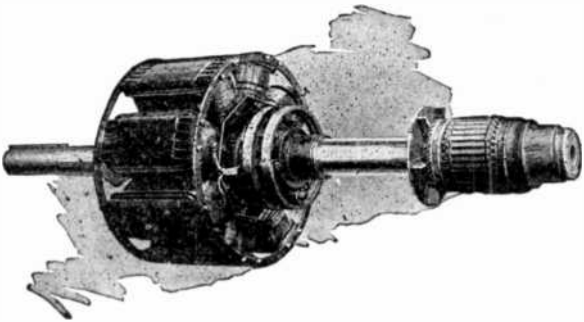


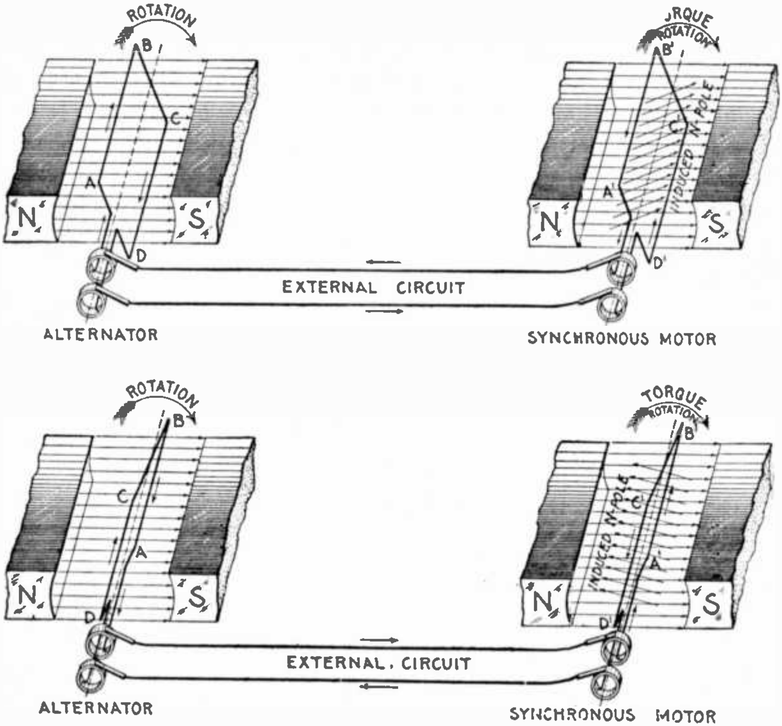
FIG. 2,486.—Allis Chalmers synchronous motor rotor and armature direct connected exciter.

1. An armature;
2. A field.

either of which may revolve. The field is separately excited with direct current.

The principles upon which such motors operate may be explained by considering the action of two elementary alternators connected in circuit, as illustrated in the accompanying illustrations, one alternator being used as an alternator and the other as a synchronous motor.

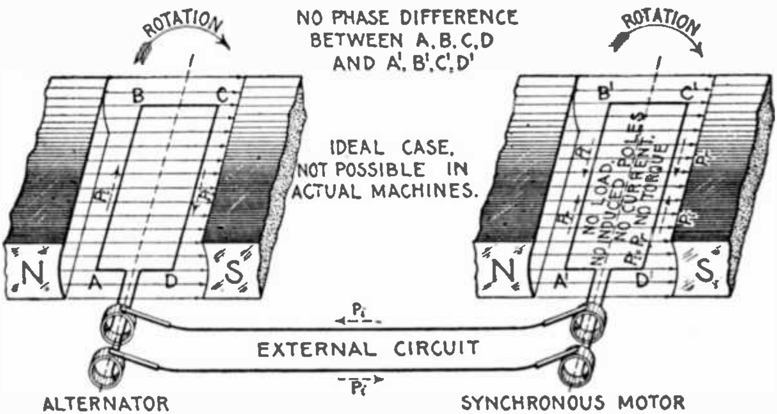
Suppose the motor, as in figs. 2,474 to 2,477, be at rest when it is connected in circuit with the alternator. The alternating current will flow through the motor armature and



FIGS. 2,487 to 2,490.—Synchronous motor principles: II. *The condition necessary for synchronous motor operation is that the motor be speeded up until it rotates in synchronism, that is, in step with the alternator.* This means that the motor must be run at the same frequency as the alternator (not necessarily at the same speed). In the figures it is assumed that the motor has been brought up to synchronism with the alternator and connected in the circuit as shown. In figs. 2,487 and 2,488 the arrows indicate the direction of the current for the armature position shown. The current flowing through the motor armature induces magnetic poles which are attracted by the field poles, thus producing a torque in the direction in which the armature is rotating. After the alternator coil passes the vertical position, the current reverses as in fig. 2,489, and the current flows through the motor armature in the opposite direction, thus reversing the induced poles as in fig. 2,490. *This brings like poles near each other, and since the motor coil has rotated beyond the vertical position the repelling action of the like poles, and also the attraction of unlike poles, produces a torque acting in the direction in which the motor is rotating.* Hence, when the two armatures move synchronously, the torque produced by the action of the induced poles upon the field poles is always in the direction in which the motor is running, and accordingly, tends to keep it in operation.

produce a reaction upon the field tending to rotate the motor armature first in one direction, then in another.

Because of the very rapid reversals in direction of the torque thus set up, there is not sufficient time to overcome the inertia of the armature,

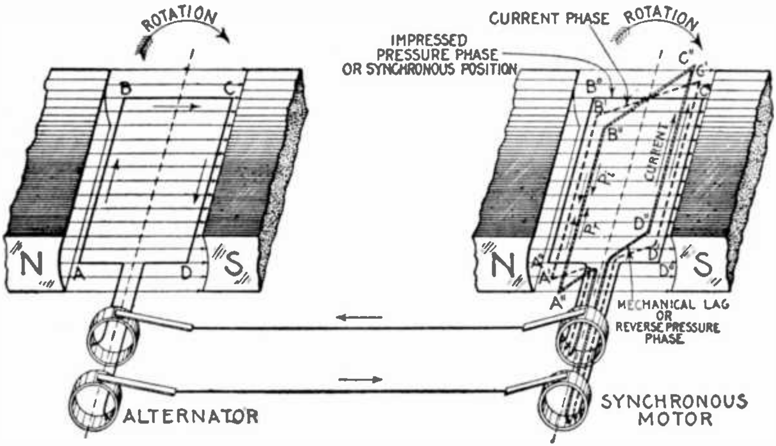


FIGS. 2,491 and 2,492.—Synchronous motor principles: III. *The current which flows through the armature of a synchronous motor is that due to the effective pressure.* Since the motor rotates in a magnetic field, a pressure is induced in its armature in a direction opposite to that induced in the armature of the alternator, and called the *reverse pressure*, as distinguished from the pressure generated by the alternator called the *impressed pressure*. *At any instant, the pressure available to cause current to flow through the two armatures, called the effective pressure, is equal to the difference between the pressure generated by the alternator or impressed pressure and the reverse pressure induced in the motor.* Now if the motor be perfectly free to turn, that is, without load or friction, the reverse pressure will equal the impressed pressure and no current will flow. This is the case of real synchronous operation, that is, not only is the frequency of motor and alternator the same, but the coils rotate without phase difference. In figs. 2,491 and 2,492, the impressed and reverse pressures are represented by the dotted arrows P_i and P_r, respectively. Since in this case these opposing pressures are equal, the resultant or effective pressure is zero; hence, there is no current. *In actual machines this condition is impossible*, because even if the motors have no external load, there is always more or less friction present; hence, in operation there must be more or less current flowing through the motor armature to induce magnetic poles so as to produce sufficient torque to carry the load. The action of the motor in automatically adjusting the effective pressure to suit the load is explained in figs. 2,493 and 2,494.

before the current reverses and produces a torque in the opposite direction hence, the armature remains stationary or, strictly speaking, it vibrates.

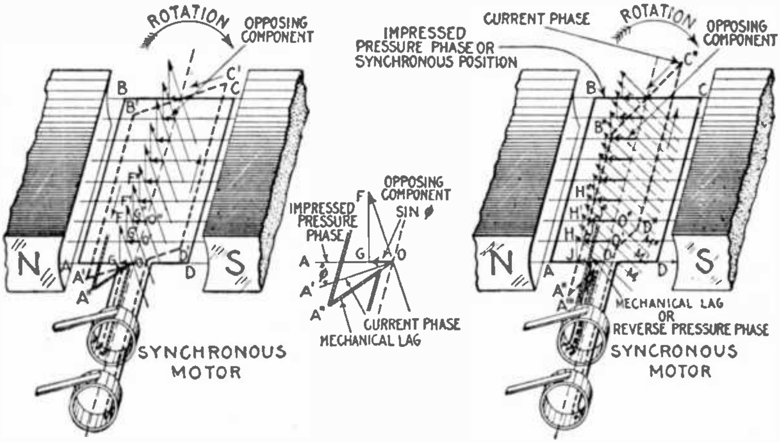
Now if the motor armature be first brought up to a speed corresponding in frequency to that of the alternator before connecting the motor in the circuit, the armature will continue revolving at the same frequency as the alternator.

The armature continues revolving, because, ***at synchronous speed, the field flux and armature current are always in the same relative position,***



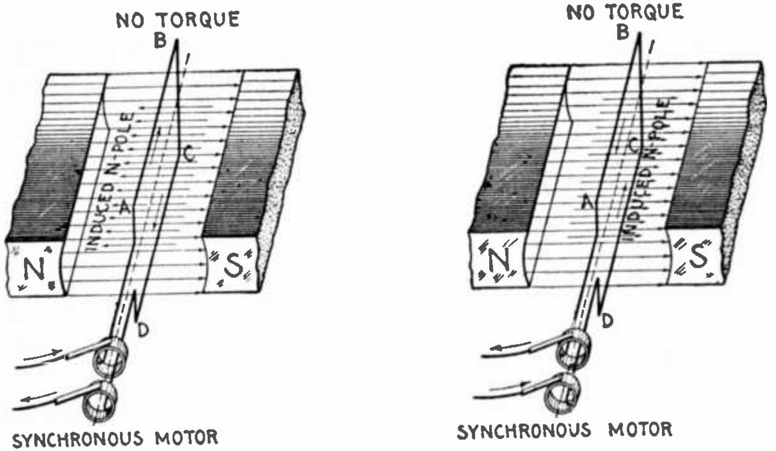
FIGS. 2,493 and 2,494.—Synchronous motor principles: IV. *A synchronous motor adjusts itself to changes of load by changing the phase difference between current and pressure.* If there be no load and no friction, the motor when speeded up and connected in the circuit, will run in true synchronism with the alternator, that is, at any instant, the coils A B C D and A°B°C°D° will be in parallel planes. When this condition obtains, no current will flow and no torque will be required (as explained in figs. 2,491 and 2,492). If a load be put on the motor, the effect will be to cause A°B°C°D° to lag behind the alternator coil to some position A″B″C″D″ and current to flow. The reverse pressure will lag behind the impressed pressure equally with the coil, and the current which has now started will ordinarily take an intermediate phase so that it is *behind the impressed pressure but in advance of the reverse pressure.* These phase relations may be represented in the figure by the armature positions shown, viz.: 1, the synchronous position A°B°C°D° representing the impressed pressure; 2, the intermediate position A′B′C′D′, the current; 3, the actual position A″B″C″D″ (corresponding to mechanical lag), the reverse pressure. From the figure it will be seen that the current phase represented by A′B′C′D′ is in advance of the reverse pressure phase represented by A″B″C″D″. Hence, by ***armature reaction***, *the current leading the reverse pressure weakens the motor field and reduces the reverse pressure,* thus establishing equilibrium between current and load. As the load is increased, the mechanical lag of the alternator coil becomes greater and likewise the current lead with respect to the reverse pressure, which intensifies the armature reaction and allows more current to flow. In this way equilibrium is maintained for variations in load within the limits of zero and 90° mechanical lag. The effect of armature reaction on motors is just the reverse to its effect on alternators, which results in marked automatic adjustment between the machines especially when a single motor is operated from an alternator of about the same size. In other words, the current which weakens or strengthens the motor field, strengthens or weakens respectively the alternator field as the load is varied.

producing a torque which always pulls the armature around in the same direction.



FIGS. 2,495 to 2,497.—Synchronous motor principles: V. *The effectiveness of armature reaction in weakening the field is proportional to the sine of the angle by which the current lags behind the impressed pressure.* If a motor be without load or friction, its armature will revolve synchronously (in parallel planes) with the alternator armature. In the figures let ABCD, represent an instantaneous position of the motor armature when this condition obtains; it will then represent the phase relationship of impressed and reverse pressures for the same condition of no load, no friction, operation. ***Now, if a light load be placed on the motor*** for the same instantaneous position of alternator armature, ***the motor coil will drop behind to some position as*** A″, fig. 2,495 (part of the coil only being shown). The reverse pressure will also lag an equal amount and its phase with respect to the impressed pressure will be represented by A″. The armature current will ordinarily take an intermediate phase, represented by coil position A′B′C′D′, inducing a field strength corresponding to the 9 lines of force OF, O′F′, etc. *The current being in advance of the phase of the reverse pressure A″, the armature reaction weakens the field,* thus reducing the reverse pressure and allowing the proper current to flow to balance the load. The amount by which the field is weakened may be determined by resolving the induced magnetic lines OF, O′F′, O″F″, etc., into components OG, GF, O′G′, G′F′, O″G″, G″F″, etc., respectively parallel and at right angles to the lines of force of the main field. Of these components, the field is weakened only by OG, O′G′, O″G″, etc. Since by construction, angle OFG = AOA′, and calling OF unity length, OG = sine of angle by which the current lags behind the impressed pressure. The construction is shown better in the enlarged diagram. For a heavier load the armature coil will drop back further to some position as A‴, fig. 2,497, and the lag of the current increase to some intermediate phase as A″B″C″D″. By similar construction it is seen that the component OG (fig. 2,495) has increased to OJ (fig. 2,497), this component thus further weakening the main field, by an amount *proportional to the sine of the angle by which the current lags behind the impressed pressure.* The increased current which is now permitted to flow, causes the induced field to be strengthened (as indicated by the dotted magnetic lines M, M′, M″, etc.), thus increasing the torque to balance the additional load.

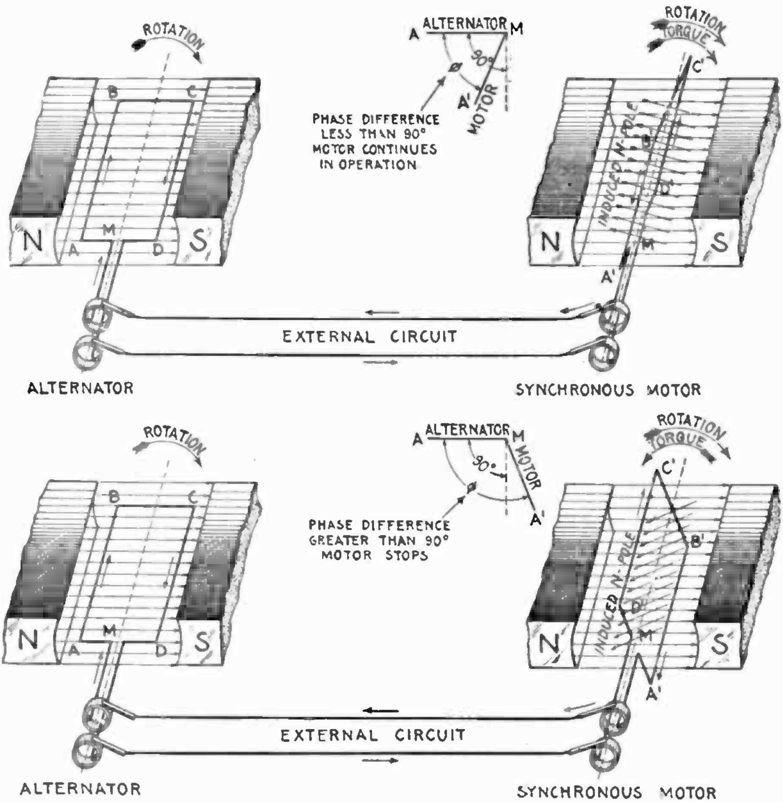
The speed of a synchronous motor is that at which it would have to run, if driven as an alternator, to deliver the number of cycles which is given by the supply alternator.



Figs. 2,498 and 2,499.—Synchronous motor principles: VI. *A single phase synchronous motor has "dead centers," just the same as a one cylinder steam engine.* Two diagrams of the motor are here shown illustrating the effect of the current in both directions. When the plane of the coil is perpendicular to the field, the poles induced in the armature are parallel to field for either direction of the current; that is to say, the field lines of force and the induced lines of force acting in parallel or opposite directions, no turning effect is produced, just as in analogy when an engine is on the dead center, the piston rod (field line of force) and connecting rod (induced line of force) being in a straight line, the force exerted by the steam on the piston produces no torque.

For instance, a 12 pole alternator running at 600 revolutions per minute will deliver current at a frequency of 60 cycles a second; an 8 pole synchronous motor supplied from that circuit will run at 900 revolutions per minute, which is the speed at which it would have to be driven as an alternator to give 60 cycles a second—the frequency of the 12 pole alternator.

The following simple formula gives the speed relations between alternators and motors connected to the same circuit and having different numbers of poles.



FIGS. 2,500 to 2,505.—Synchronous motor principles: VII. *An essential condition for synchronous motor operation is that the mechanical lag be less than* 90°. Figs. 2,500 and 2,502 represent the conditions which prevail when the lag of the motor armature A'B'C'D' is anything less than 90°. As shown, the lag is almost 90°. The direction of the current and induced poles are indicated by the arrows. *The inclination of the motor coil is such that* ***the repulsion of like poles*** *produces a torque* ***in the direction of rotation,*** thus tending to keep motor in operation. Now, in figs. 2,503 and 2,505 for the same position of the alternator coil ABCD, *if the lag be greater than* 90°, *the inclination of the motor coil* A'B'C'D' *is such that at this instant* ***the repulsion of like poles*** *produces a torque in a direction* ***opposite*** *to that of* ***the rotation,*** *thus* ***tending to stop the motor.*** When the motor armature has fallen out of step this action will cause it to slip with reference to the alternator, or run at a slower speed. When it has slipped a full half cycle the torque will again be forward: the resultant torque will therefore equal zero. Hence, it will have no turning power to overcome load and losses in itself and will therefore quickly come to rest.

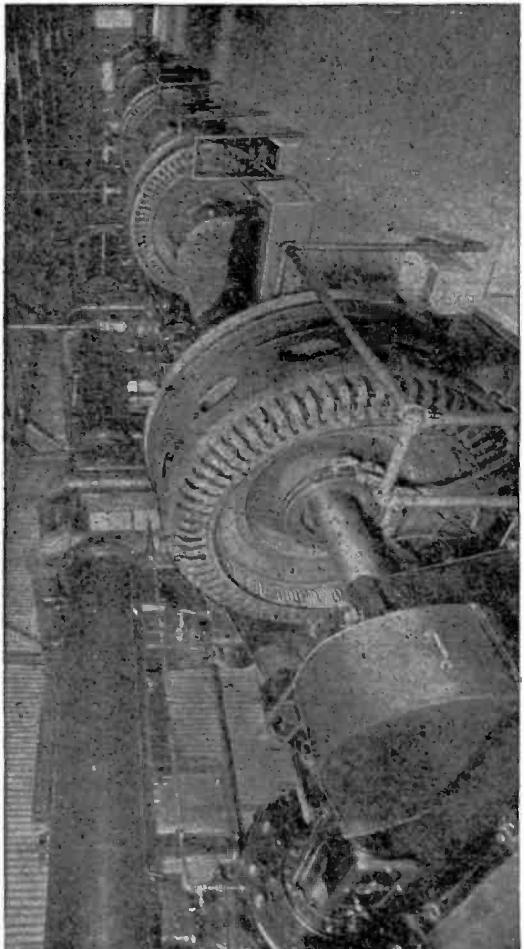


FIG. 2,506.—Six 300 *h.p.* Westinghouse synchronous motors driving air compressors furnishing compressed air for subway construction. These motors are extensively used for driving air and ammonia compressors, pulp grinders, pumps and similar applications. They are built 50 and 60 cycles, 2 and 3 phase, 100 *h.p.* at 400 *r.p.m.* to 5000 *h.p.* at 100 *r.p.m.*

$$r = \frac{P \times R}{p}$$

in which

r = Revolutions per minute of the motor;
p = Number of poles of the motor;
R = Revolutions per minute of the alternator;
P = Number of poles of the alternator.

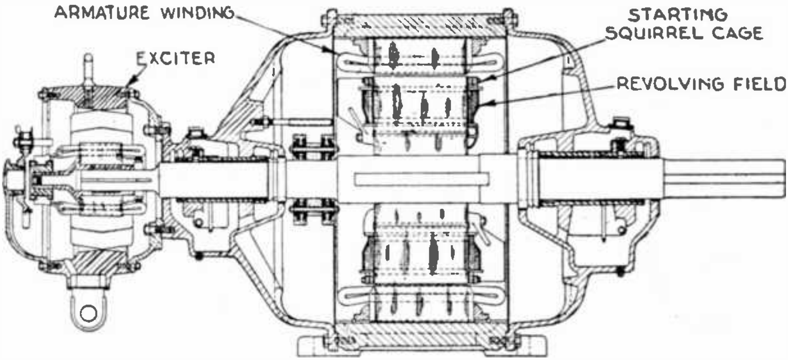
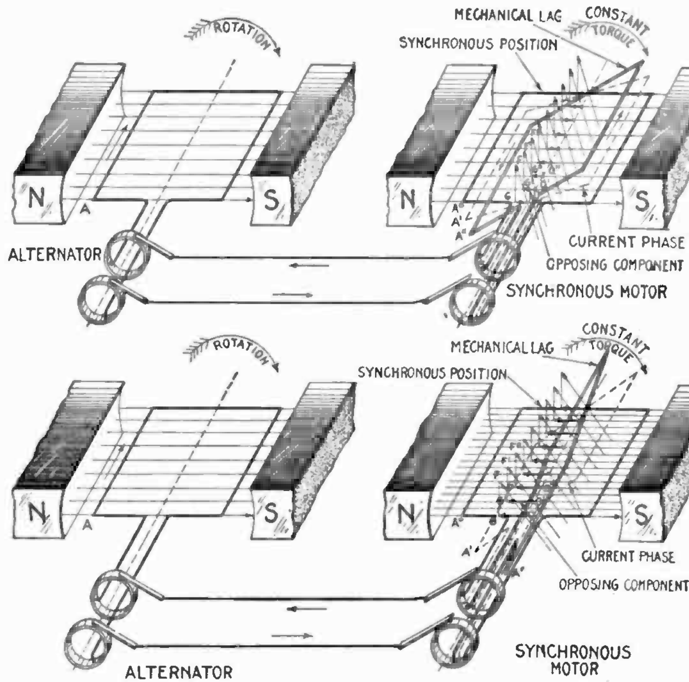


FIG. 2,507.—General Electric general purpose synchronous motor "7500 Series" adapted for general purpose application and will drive any load whose torque requirements have been successfully met by a standard squirrel cage induction motor. *In construction*, the field spider is built from heavy punched steel laminations riveted to form a solid mass. The laminated steel pole pieces are assembled under high pressure and are dovetailed to the spider. Small cast air fans also cover the dovetailed joints, preventing lateral movement of the pole pieces. The amortisseur windings are composed of round brass and copper bars, firmly silver soldered to the end rings. The cast iron collector rings are well insulated from the shaft. The rotor is designed for operation at 1, .9 or .8 power factor. For operating at leading power factor, the air gap is generally decreased by the use of shims which can easily be inserted or removed after installation. The air gap is never as small as that of an induction motor of the same rating. The same shunt wound exciter is furnished for a given motor, whether rated at 1, .9 or .8 power factor. The exciter voltage and motor excitation are adjusted by means of an exciter field rheostat. The exciter may be easily removed from the motor shaft when desired.

Ques. If the field strength of a synchronous motor be altered, what effect does this have on the speed, and why?

Ans. The speed does not change (save for a momentary variation to establish the phase relation corresponding to



FIGS. 2,503 to 2,511.—Synchronous motor principles: VIII. *If the torque and current through the motor armature be kept constant, strengthening the field will increase the mechanical lag, and the lead of the current with respect to the reverse pressure.* In the figures, let A, be an instantaneous position of the alternator coil, A°, synchronous position of motor coil, A′, position corresponding to current phase, A″, actual position or mechanical lag of motor coil behind alternator coil necessary to maintain equilibrium. In fig. 2,509, let A′ and A″, represent respectively the relation of current phase and mechanical lag *corresponding to a certain load and field strength.* For these conditions OG, O′G′, O″G″, etc., will represent the components of the induced lines of force in opposition to the motor field, that is, *they indicate the intensity of the armature reaction at the instant depicted.* Now, assume the field strength to be ***doubled***, as in fig. 2,511, *the motor **load and current being maintained constant.*** Under these conditions, the armature reaction must be doubled to maintain equilibrium; that is, the components OG, O′G′, etc., fig. 2,511, must be twice the length of OG, O′G′, etc., fig. 2,508. Also since the current is maintained constant, the induced magnetic lines OF, O′F′ are of same length in both figures. Hence, in fig. 2,511 the plane of these components is such that their extremities touch perpendiculars from G, G′, etc., giving the other components FG, F′G′, etc. The plane A′, normal to OF, O′F′, etc., gives the current phase. By construction, the phase difference between A° and A′, is such that sin A°OA′, (fig. 2,511) $=2\times$sin A°OA′, (fig. 2,509). That is, doubling the field equilibrium), because the motor has to run at the same frequency as the alternator.

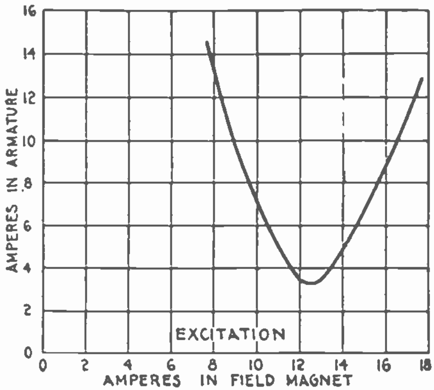


Fig. 2,512.—Diagram illustrating method of representing the performance of synchronous motors. The *V shaped curve* is obtained by plotting the current taken by motor under different degrees of excitation, the power developed by the motor remaining constant. The current may be made to lag or lead while the load remains constant, by varying the excitation. A certain value may be reached by varying the excitation, which will give a minimum current in the armature; this is the condition of unity power factor. If now the excitation be diminished the current will lag and increase in value to obtain the same power; if the excitation be increased the current will *lead* and increase in value to obtain the same power. The results plotted for several values of the excitation current will give the V curve as shown. This is an actual curve obtained by Morley on a 50 *kw.* machine running unloaded as a motor. Other curves situated above this one may be obtained for various loadings of the motor.

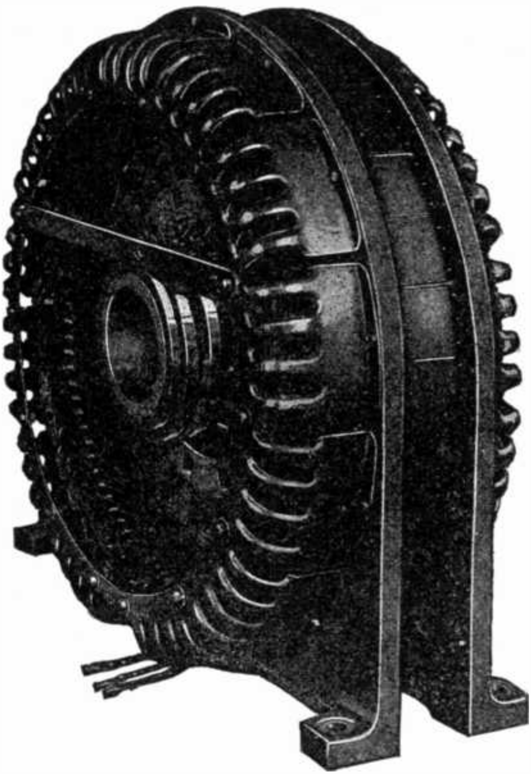
Ques. How does a synchronous motor adjust itself to changes of load and field strength?

Ans. By changing the phase difference between the current and pressure.

If, on connecting a synchronous motor to the mains, the excitation be

Figs. 2,508 to 2,511.—*Text continued.*

strength causes an increase of current lag such that the sine of the angle of this lag is doubled. Since the intensity of the armature reaction depends on the lead of the current with respect to the reverse pressure, the mechanical lag of the coil must be increased to some position as A″, (fig. 2,511), such as will give an armature reaction of an intensity indicated by the components OG, O′G′, etc.



too weak, so that the voltage is lower than that of the supply, this phase difference will appear resulting in lagging wattless current, since the missing magnetization has, as it were, to be supplied from an external source. A phase difference also appears when the magnetization is too strong.

Ques. State the disadvantages of synchronous motors.

Ans. A synchronous motor requires an auxiliary power for starting, and will stop if, for any reason, the synchronism be destroyed; collector rings and brushes are required. For some purposes synchronous motors are not desirable, as for driving shafts in small workshops having no other power available for starting, and in cases where frequent starting, or a strong torque at starting is necessary. A synchronous motor has a tendency to *hunt** and requires intelligent attention; also an

Fig. 2,513.—General Electric slow speed small synchronous motor "6000 Series" adapted to meet the demand for slow speed synchronous motors suited to the direct drive of reciprocating compressors.

*NOTE.—See Hunting of Synchronous Motors, page 1,765.

exciting current which must be supplied from an external source.

Ques. State the advantage of synchronous motors.

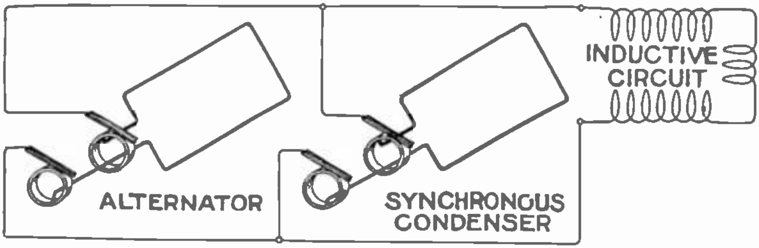


FIG. 2,514.—Diagram illustrating the use of a synchronous motor as a condenser. If a synchronous motor be sufficiently excited the current will lead. Hence, if it be connected across an inductive circuit as in the figure and the field be over excited it will compensate for the lagging current in the main, thus increasing the power factor. If the motor be sufficiently over excited the power factor may be made unity, the minimum current being thus obtained that will suffice to transmit the power in the main circuit. A synchronous motor used in this way is called a *rotary condenser* or *synchronous condenser*. This is especially useful on long lines containing transformers and induction motors.

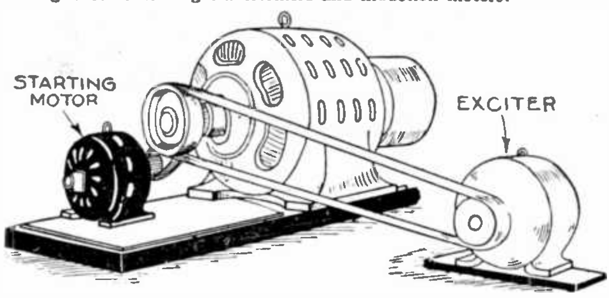


FIG. 2,515.—***Auxiliary starting type*** synchronous motor showing exciter and starting induction motor. The induction motor must have at least one pair of poles less than the synchronous motor, otherwise the synchronous motor could not be brought up to synchronous speed. This is because the *speed of an induction motor is somewhat less than synchronous speed*. The induction motor should be wound for the same voltage and number of phases as the synchronous motor, so that the same bus bars may be used to feed both motors.

Ans. The synchronous motor is desirable for large powers where starting under load is not necessary. Its power factor may be controlled by varying the field strength. The power factor can be made unity and, further, the current can be made to lead the pressure.

A synchronous motor is frequently connected in a circuit solely to improve the power factor. In such cases it is often called a "condenser motor" for the reason that its action is similar to that of a condenser.

The design of synchronous motors proceeds on the same lines as that of alternators, and the question of voltage regulation in the latter becomes a question of power factor regulation in the former.

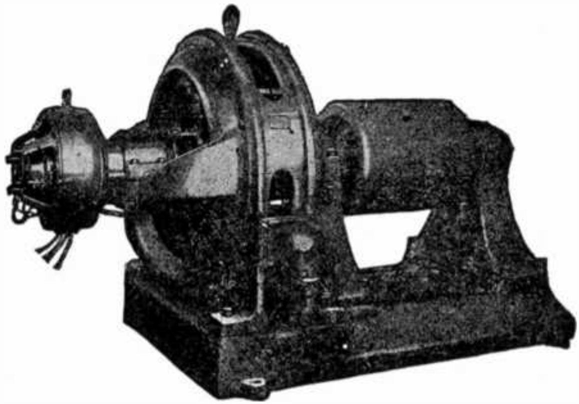


FIG. 2,516.—General Electric 12 pole, 600 *r.p.m.*, 250 *h.p.* synchronous motor with 3 *kw.* 125 volt exciter.

Ques. For what service are they especially suited?

Ans. For high pressure service.

High voltage current supplied to the armature does not pass through a commutator or slip rings; the field current which passes through slip rings being of low pressure does not give any trouble.

Ques. How do synchronous and induction motors compare as to efficiency?

Ans. Synchronous motors are usually the more efficient.

Hunting of Synchronous Motors.—Since a synchronous motor runs practically in step with the alternator supplying it with current when they both have the same number of poles, or some multiple of the ratio of the number of poles on each machine, it will take an increasing current from the line as its speed drops behind the alternator, but will supply current to

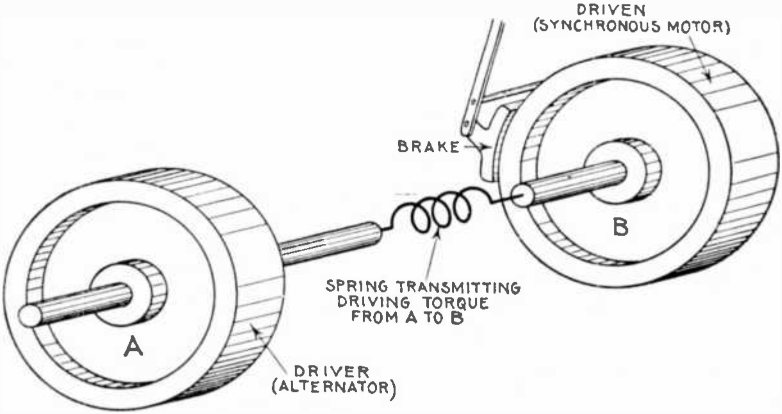


FIG. 2,517.—Mechanical analogy illustrating "hunting." The figure represents two fly wheels connected by a spring susceptible to tortion in either direction of rotation. If the wheels A and B, be rotating at the same speed and a brake be applied, say to B, its speed will diminish and the spring will coil up, and if fairly flexible, more than the necessary amount to balance the load imposed by the brake; because when the position of proper torque is reached, B, is still rotating slightly slower than A, and an additional torque is required to overcome the inertia of B, and bring its speed up to synchronism with A. Now before the spring stops coiling up the wheels must be rotating at the same speed. When this occurs the spring has reached a position of too great torque, and therefore exerting more turning force on B, than is necessary to drive it against the brake. Accordingly B, is accelerated and the spring uncoils. The velocity of B, thus oscillates above and below that of A, when a load is put on and taken off. Owing to friction, the oscillations gradually die out and the second wheel takes up a steady speed. A similar action takes place in a synchronous motor when the load is varied.

the line as a dynamo if for any reason the speed of the alternator should drop behind that of the motor, or the current wave lag behind, which produces the same effect, and due to additional self-induction or inductance produced by starting up or overloading some other motor or rotary converter in the circuit. When the motor is first taking current, then giving current back to the line, and this action is continued periodically, the motor is said to be *hunting*.

Ques. What term is applied to describe the behavior of the current when hunting occurs?

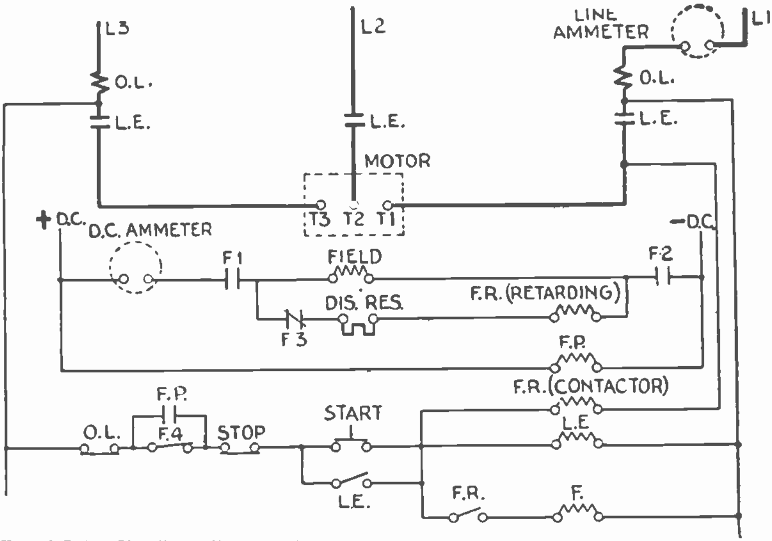


FIG. 2,518.—Simplified diagram of General Electric *across the line* starter. *In operation*, pushing the start button energizes the line contactor coil LE, closing the line contactor and connecting L1, L2, and L3, to the motor. The interlock LE, closes at the same time as the line contactor and forms a holding circuit for the line contactor, so that the push button may be released. While the motor is accelerating the field circuit is closed through the normally closed pole F3, of the field contactor, through the discharge resistor and the retarding coil FR, of the field relay. This holds the interlock FR, open until the motor approaches synchronism. At the time the line contactor LE, closes, the contactor coil FR, is energized and tends to close the interlock FR. As the motor accelerates, the induced field current through the retarding coil FR, decreases, and releases the interlock FR, when the motor nears synchronism. After a few seconds delay the interlock FR, closes, energizing the contactor coil F, causing F1 and F2, to close and F3 and F4, to open. The closing of F1 and F2, applies excitation to the motor field, completing the starting operation. The opening of F3, opens the discharge circuit of the motor field. The opening of F4, allows FP, to shut down the equipment in case of failure of voltage on the exciter bus. FP, must have closed its contacts before the field contactor opens F4, necessitating that excitation voltage be available before attempting to apply field.

Ans. The term *surging* is given to describe the current fluctuations produced by hunting.

Magnetic Clutch Type Synchronous Motor.—This type motor

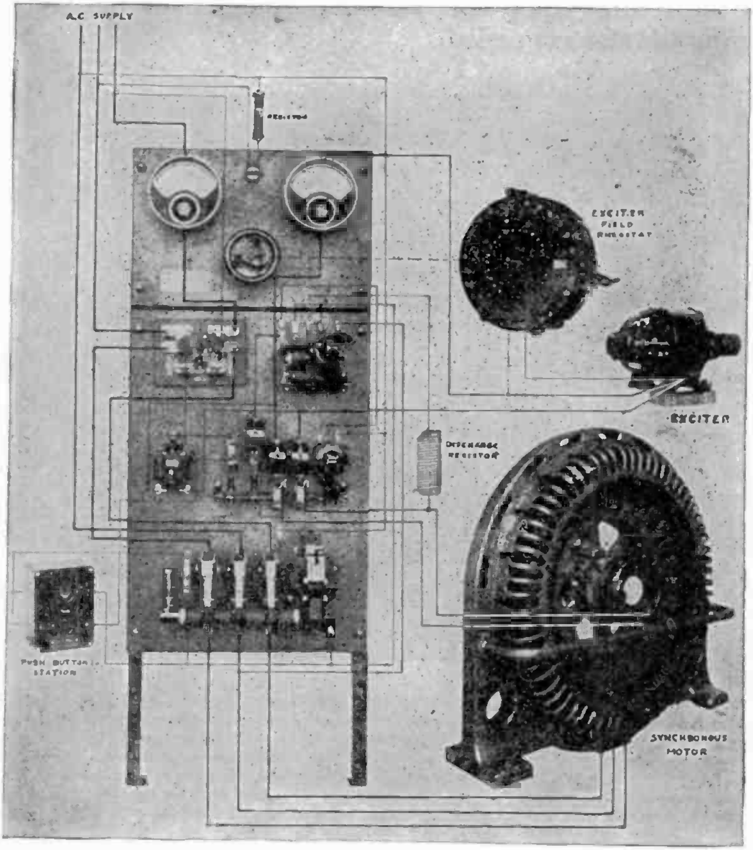


FIG. 2,519.—Pictured representation of General Electric *across the line* starter showing its connections and relations to a synchronous motor and exciter.

is so constructed that the field magnets are free to rotate on shaft except when engaged magnetically by a clutch. *In operation*, the motor is started in the same manner as the standard synchronous motor when started under light load conditions, as the control equipment prevents excitation of the clutch during the starting period.

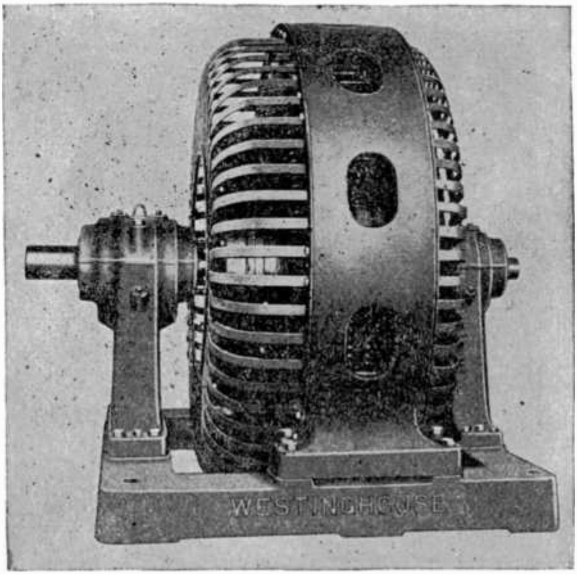


FIG. 2,520.—Westinghouse magnetic clutch type synchronous motor. This type combines in one machine the high starting torque of the wound rotor induction motor and the desirable operating characteristics of the synchronous motor. This is effected by incorporating the magnetic clutch, shown in fig. 2,522, with a standard synchronous motor. This motor is particularly adapted for driving, crushing and grinding machinery, pulp beaters, flour mills, rolling mills, and any type of machinery requiring high starting torque. The motor may be operated as a synchronous condenser for power factor correction by simply opening the clutch excitation circuit, which disconnects the load

Operation of the motor starter connects the motor to the line and applies field excitation, the field freely rotating upon roller bearings between the shaft and field spider. The clutch can now be excited at the will of the operator by pressing the "*in*" push button. This starts rotation of the motor driven drum of the clutch control which closes the clutch coil circuit contactor, placing *d.c.* excitation on the clutch coil.

As the drum rotates, successive steps of resistance in series with the clutch coil are cut out, increasing the exciting current to the clutch coil

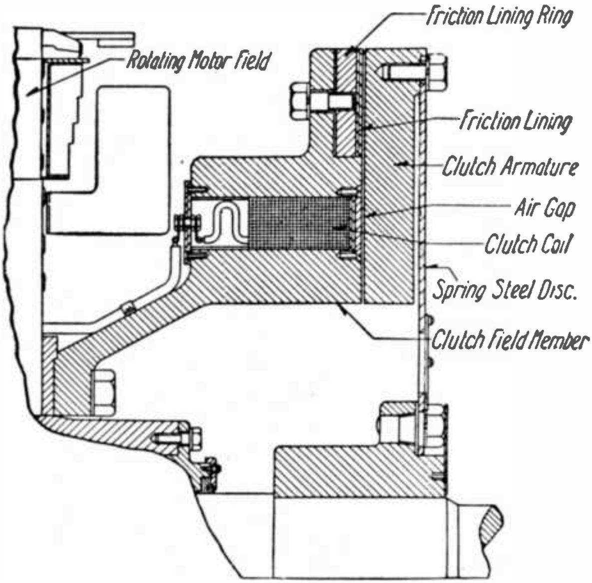


FIG. 2,521.—Sectional view of Westinghouse magnetic clutch type synchronous motor built in magnetic clutch. ***In construction,*** positive clearance between clutch plates when the clutch is unexcited is assured by the use of the spring plate construction. The armature member of the clutch is mounted on a steel disc which has sufficient flexibility to allow the clutch faces to make contact when the clutch coil is excited, but which will spring back into normal position when the clutch coil is released. Dragging of the clutch faces when the coil is not excited cannot take place. The coil is secured in place in the field member by means of a brass ring. Exciting coils can be wound for either 125 or 250 volts direct current. The energy requited for excitation is very low, ranging from 250 watts for the smallest to 750 watts for the largest size clutch.

and causing the two halves of the clutch to be drawn together. This brings their friction surfaces into contact, and thus the driven half of the clutch is brought up to synchronous speed.

The rate of acceleration of the load can be adjusted by means of the clutch rheostat, which is used for setting the exciting current at a predetermined value.

When it is desirable to have automatic operation of the clutch, the "*in*" button is left depressed, which allows the clutch to engage auto-

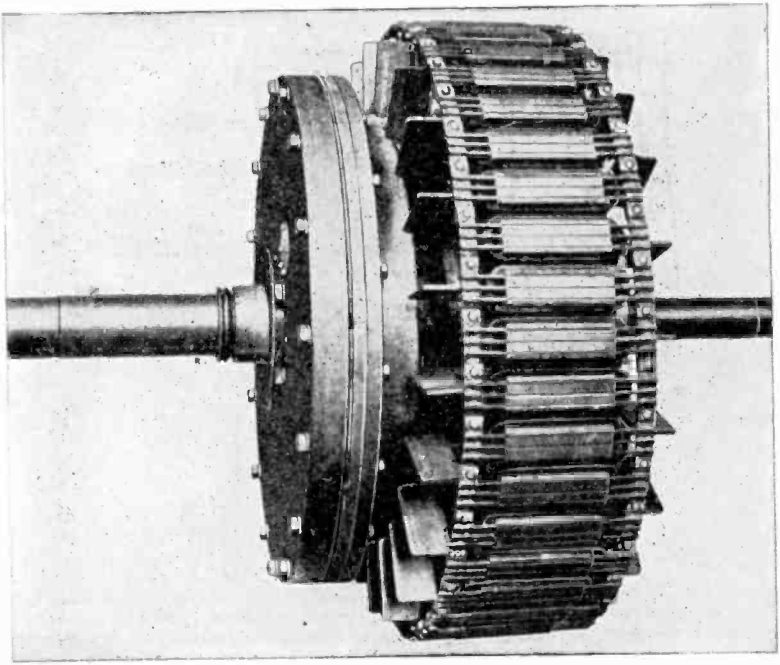


FIG. 2.522—Rotor of Westinghouse magnetic clutch type synchronous motor showing magnetic clutch, welded damper squirrel cage, field, fan, etc.

matically after the motor starter has brought the motor to synchronous speed and applied field excitation.

Stopping of both motor and load is accomplished through operation of the motor starter.

The mechanical analogy of hunting illustrated in fig. 2,517 will help to an understanding of this phenomenon. In alternating current circuits a precisely similar action takes place between the alternators and synchronous motors, or even between the alternators themselves.

Characteristics of Synchronous Motors

****Starting.***—The motor must be brought up to synchronous speed without load, a *starting compensator* being used. If provided with a self-starting device, the latter must be cut out of circuit at the proper time. The starting torque of motor with self-starting device is very small.

Running.—The motor runs at synchronous speed. The maximum torque is several times full load torque and occurs at synchronous speed.

Stopping.—If the motor receive a sudden overload sufficient to momentarily reduce its speed, it will stop; this may be brought about by momentary interruption of the current, sufficient to cause a loss of synchronism.

Effect Upon Circuit.—In case of short circuit in the line the motor acts as a dynamo and thus increases the intensity of the short circuit. The motor impresses its own wave form upon the circuit. Over excitation will give to the circuit the effect of *capacity*, and under excitation, that of *inductance*.

Power Factor.—This depends upon the field current, wave form and hunting. The power factor may be controlled by varying the field excitation.

Necessary Auxiliary Apparatus.—Power for starting, or if self-starting, means of reducing the voltage while starting; also, field exciter, rheostat, friction clutch, main switch and exciter switch, instruments for indicating when the field current is properly adjusted.

Adaptation.—If induction motors be connected to the same line with a synchronous motor that has a steady load, then the field of the synchronous motor can be over excited to produce a leading current, which will counteract the effect of the lagging currents induced by the induction motors. Owing to the weak starting torque, skilled attendance required,

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*NOTE.—Fig. 2,515 shows the auxiliary motor method of starting. ***Another method*** is to provide the motor with a starting winding in the pole faces as shown in fig. 2,486. This is an auxiliary squirrel cage or *amortisseur* winding and consists of a number of metal rods embedded in the pole faces and interconnected with and brazed to short circuiting rings. ***The action*** of the squirrel cage is fully explained in the chapter on squirrel cage induction motors. The squirrel cage also tends to damp out oscillations of the armature (called "hunting") and because of this action the winding is sometimes called a "damping winding."

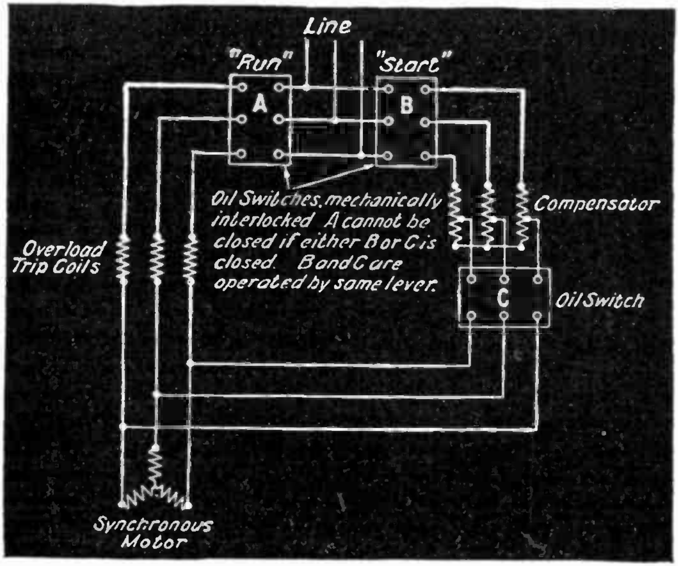


FIG. 2,523.—Starting connections for self-starting synchronous motor. ***In starting*: 1**, Open field switch completely if the excitation voltage be 125 volts; if the excitation voltage of the motor be higher than 125 volts, the field switch should not be opened completely but left in the clips connected to the discharge resistance. This prevents any high induced voltage across the collector rings. ***Exception*:** If the motor be part of a motor generator set (other than a frequency converter set) the field switch should be left in the clips connected to the discharge resistance irrespective of the degree of field excitation. Note that frequency degree converter sets should be started in accordance with the general rule given above; **2**, Throw compensator lever to "start" position. (If oil switches be used, close the switch marked "start.") **3**, After the motor has reached constant speed close the field switch; the field rheostat having been previously adjusted to give a field current corresponding approximately to no load, normal voltage, with machine running as a generator. **4**, Throw compensator lever quickly to the "run" position. (If oil switches be used, open the switch marked "start," and after this, as quickly as possible, close the switch marked "run.") ***Cautions*: 1**, Do not touch collector rings or brushes when the motor is being started. An induced pressure of about 2,000 volts exists across the rings at the moment of starting. This voltage decreases as the motor speeds up, reaching zero at full speed. **2**, The motor should be started on the lowest tap of the compensator that will start it promptly and bring it to full speed in about one minute. If two or three minutes are consumed in coming to full speed, there is danger of burning the squirrel cage winding. *Special cases.* There are a few instances where requirements of torque and line current, or perhaps a demand for a high excitation voltage (which involves a high induced voltage at starting) make it necessary to modify the procedure in starting. ***Closing running switch before synchronizing.*** There are rare cases where severe requirements of "pull-in" torque make it necessary to close the running switch, throwing on full line pressure before the field switch is closed. That is operation **3** above should follow **4**. ***Closing field current through resistance.*** There are two occasions for closing the field circuit through a resistance as part of the starting procedure. In one case the object is to increase the torque near full speed; in the other, to prevent high induced pressure across the collector rings at starting. With the proper value of resistance across the collector rings the torque near full speed is increased. A change and the liability of the motor to stop under abnormal working conditions, the synchronous motor is not adapted to general power distribution, but rather to large units which operate under a steady load and do not require frequent starting and stopping.

Super-Synchronous Motors.—The term *super-synchronous* motor is applied to a synchronous motor in which the armature, or usual stator, is arranged so that it can rotate around the shaft, but is normally held stationary by a brake around its outer periphery.

When starting up the motor, the brake is first released, and power is applied to the motor from the auto-transformer taps. Now, since the rotor is connected to the load, while the armature is entirely free to rotate except for the slight bearing friction, the armature begins to revolve around the field, instead of the field revolving inside the armature, as in the standard motor. The armature is brought up to full speed and field applied, so that the motor is running in synchronism and capable of exerting its full pull out torque. To transfer rotation from the armature to the rotor the brake is now applied gradually, the relative motion remaining at synchronism and the armature comes to rest while the rotor and load come up to synchronous speed. This motor, therefore, is capable of starting any load so long as the torque required is less than the pull out torque. Fig. 2,524 shows a motor of the super-synchronous type.

A large number of super-synchronous machines are operating in cement mills, and two 500 *h.p.* motors are in use driving brass rolling mills.

FIG. 2,523.—*Continued*
from this resistance in either direction will decrease the torque. At starting, however, any value of resistance will decrease the torque which the motor would develop with collector rings open. Hence, when a motor at the time it is purchased is required to pull into synchronism a large percentage of normal load, or when conditions arise in service where the "pull-in" torque requirements prove to be greater than were anticipated, the above scheme is sometimes resorted to. An accurate and convenient way of determining the proper resistance is to bring the motor to constant speed at full line voltage with the load it has to pull into synchronism; then by means of a water box connected across the collector rings, determine the resistance which will increase the speed to the highest value. This will be the proper resistance. The field discharge resistance in such case is increased to the proper value and capacity for this added service. Here, the switching procedure is only slightly modified. When the motor is running on the last tap, or on the line, as the case may be,—that is, when in the standard case, the next operation would be to close the field switch. This switch should be closed on the first point, thereby throwing the resistance across the field. A moment later say 5 or 10 seconds, close the field switch entirely. On a given machine, the higher the excitation voltage for which the field winding is designed, the higher the induced voltage across the collector rings at starting. Motors which are designed for normal excitation voltages higher than 125 volts, or those which form part of motor generator sets other than frequency converter sets, should have the field winding short circuited through the discharge resistance at starting. This will prevent the high induced voltage across the collector rings. It is standard practice to make all discharge resistances for synchronous motors of ample capacity for this service.

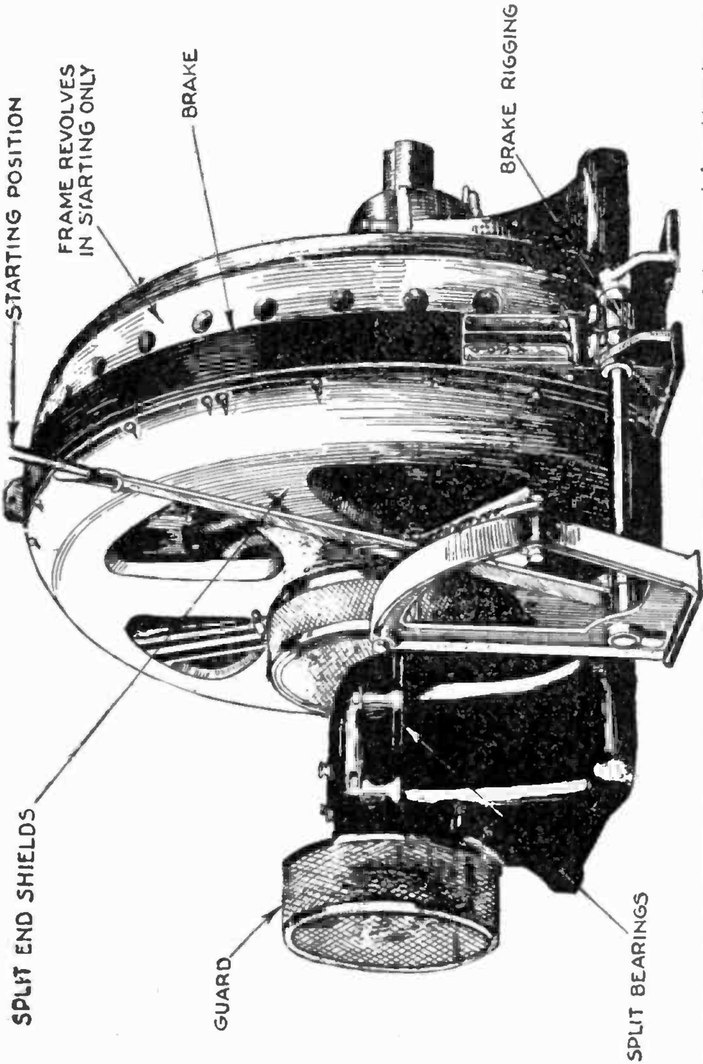


FIG. 2,524.—General Electric super-synchronous motor. ***In operation,*** with brake released the stator is brought up to synchronous speed with the rotor stationary. As the brake is applied the stator slows down and the rotor speeds up with the full pull out torque available for starting duty. When the stator stops, the rotor is up to synchronous speed and the motor functions in the normal manner.

TEST QUESTIONS

1. *What is a synchronous motor?*
2. *What does the term* synchronous *mean?*
3. *Is a single phase synchronous motor self starting?*
4. *What is the adaptation of synchronous motors?*
5. *Will a single or polyphase alternator operate as a synchronous motor?*

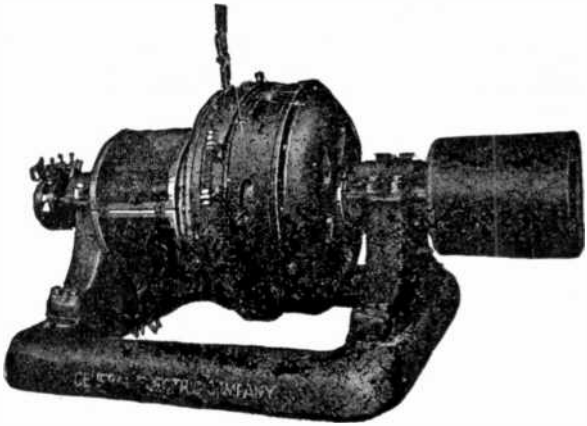


FIG. 2,525.—General Electric Form SD, super-synchronous motor; 8 pole, 100 *h.p.* 900 *r.p.m.* 220 volt.

6. *What are the two essential elements of a synchronous motor?*
7. *What condition is necessary for synchronous motor operation?*
8. *How does a synchronous motor adjust itself to changes of load?*
9. *Give a formula for the speed of a synchronous motor.*

10. *If the field strength of a synchronous motor be altered, what effect does this have on the speed, and why?*
11. *State the advantages and disadvantages of synchronous motors.*
12. *For what service are synchronous motors especially suited?*
13. *Define the term* hunting.
14. *What term is applied to describe the behavior of the current when hunting occurs?*
15. *Give the characteristics of synchronous motors.*
16. *What is a super-synchronous motor?*

CHAPTER 56

Polyphase Induction Motors

1. Squirrel Cage Type

By definition a squirrel cage motor is an **asynchronous*** **motor**, *in which the currents supplied are led through the field coils only*, and the armature, not being connected to the external circuit, is rotated by currents induced by the varying field set up through the field coils.

The operation of a polyphase induction motor depends on the production of a **rotating magnetic field** by passing alternating currents through the field magnets. This means that the poles produced by the alternating currents *are constantly changing their positions relative to the field winding, the latter being stationary*; hence, the term *rotating magnetic field*.

An optical analogy of a rotating magnetic field may be obtained by watching a flasher sign having a rotating border.

The polyphase squirrel cage type induction motor possesses many inherent advantages which have made it one of the most extensively used types of electrical apparatus.

Extremely simple in construction and reliable in operation, it may be built so rugged as to be used under the most trying conditions, and in exposed locations. The squirrel cage type, having no wearing parts except the bearings, assures freedom from sparking so that it may be placed with safety where, on account of the fire hazard, a direct current machine would be dangerous.

*NOTE.—***The term asynchronous** means *not coinciding with respect to time, not occurring simultaneously*, hence, briefly, ***not in step.*** Accordingly, an ***asynchronous motor*** is a motor which *does not run in step with the alternations of the current.*

As squirrel cage motors are the simplest form of electric motors and as they have been thoroughly standardized, the differences between various makes lie principally in the details of mechanical construction and in the operating characteristics.

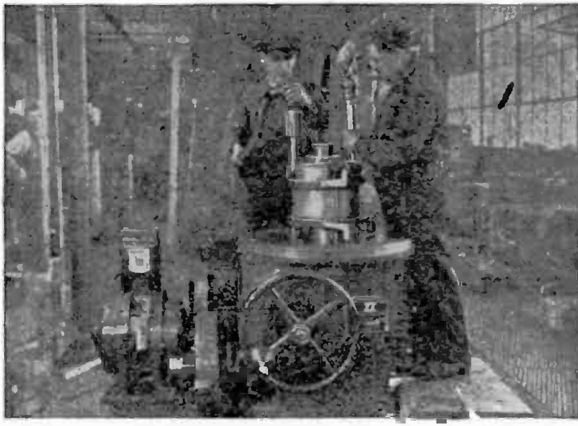


FIG. 2,526.—***Reliance induction motor construction 1.*** Completing the assembly of field punchings with steel end flanges by riveting. One end of rivet is heated electrically and then upset to obtain tight and rigid cores.

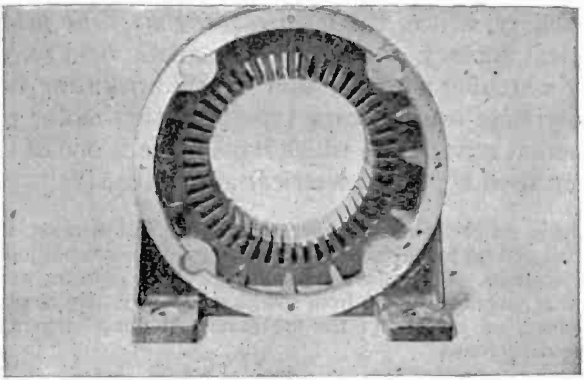


FIG. 2,527.—***Reliance induction motor construction 2.*** Field laminations assembled with end flanges and ready for winding. End flanges are cast steel. The feet are cast integral with the steel flanges. All machine work on the flanges is done after assembly with the laminations.

Ques. Describe briefly the operation of a single phase motor.

Ans. A single phase current being supplied to the field magnets, an *oscillating* field* is set up. A single phase motor is not self-starting; but when the armature has been set in motion *by external means*, the reaction between the magnetic field and the induced currents in the armature being no longer zero, a torque is produced tending to turn the armature.

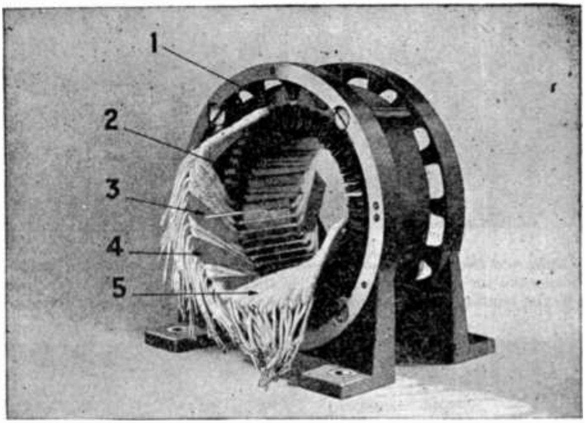


FIG. 2,528.—***Reliance induction motor construction 3.*** The details are: 1, slot cell insulation extends ½ in. beyond slot; 2, fibre separator inserted in slot between coils; 3, slot stick; 4, oiled muslin used for insulating coils between phases; 5, heads of coils are taped with linen tape.

The current flowing through the armature produces an alternating polarity such that the attraction between the unlike armature and field poles is always in one direction, thus producing the torque.

Ques. Why is a single phase induction motor not self-starting?

*NOTE.—"The word *oscillating* is becoming specialized in its application to those currents and fields whose oscillations are being damped out, as in electric 'oscillations.' But for this, we should have spoken of an oscillating field."—*S. P. Thompson*. The author believes the word *reciprocating*, best describes the single phase field, and should be here used.

Ans. Because the field is *reciprocating* instead of *rotating*.

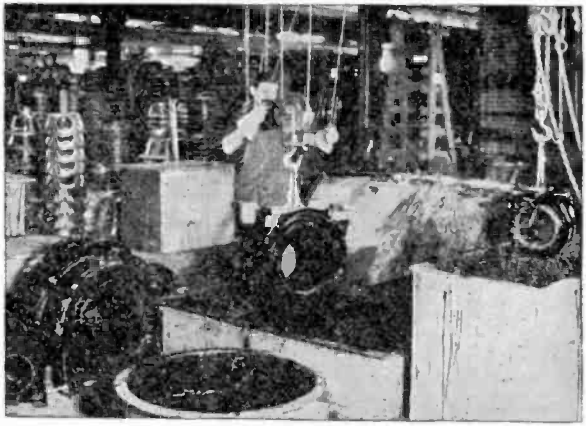


FIG. 2,529.—***Reliance induction motor construction 4.*** The complete field is immersed while hot in special insulating varnish. It is then baked for 12 hrs. To insure thorough protection to the windings four full varnish treatments are given, each followed by baking.

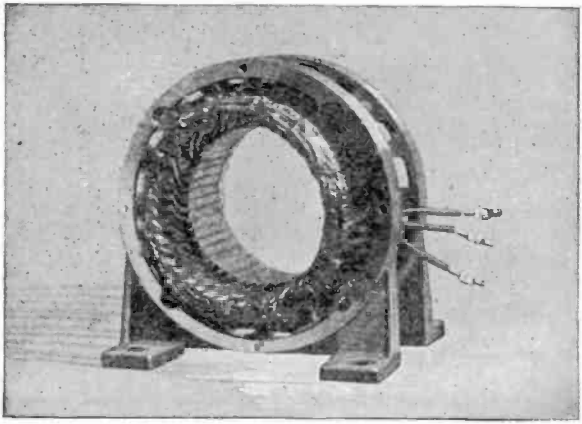


FIG. 2,530.—***Reliance induction motor construction 5.*** Complete field with windings.

With respect to torque production the field may be regarded as reciprocating when the armature is at rest and rotating when in motion.

Ques. What provision is made for starting single phase induction motors?

Ans. Apparatus is supplied for "splitting the phase" (later described in detail) of the single phase current furnished, converting it temporarily into a two phase current, so as to obtain

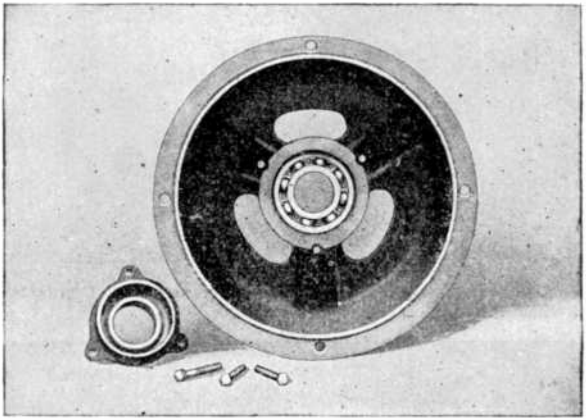


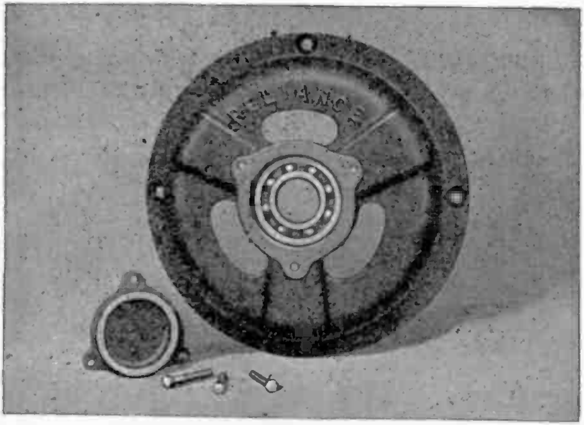
FIG. 2,531 to 2,535.—*Reliance induction motor construction 6.* Bearing bracket with outside bearing cap removed. Bearings are interchangeable for both ends of the motor.

a *rotating field* which is maintained till the motor is brought up to speed. The phase splitting device is then cut out and the motor operated with the *reciprocating field* produced by the single phase current.

Ques. Describe briefly the operation of a polyphase induction motor.

Ans. Its operation is due to the production of a *rotating magnetic field* by the polyphase current furnished.

This field "rotating" in space about the axis of the armature induces currents in the latter. The reaction between these currents and the rotating field creates a torque which tends to turn the armature, whether the latter be at rest or in motion.



FIGS. 2,536 to 2,540.—***Reliance induction motor construction 7.*** Bearing bracket. Extra strength is obtained by the channel shaped sections.

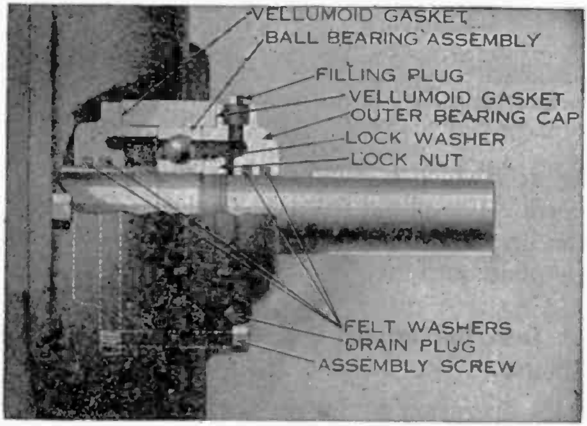


FIG. 2,541.—***Reliance induction motor construction 8.*** Bearing mounting.

Ques. Why are induction motors called "asynchronous"?

Ans. Because the armature does not turn in synchronism with the rotating field, or, in the case of a single phase induction motor, with the reciprocating field (considering the latter in the light of a rotating field).

Ques. How does the speed vary?

Ans. It is slower (more or less according to load) than the

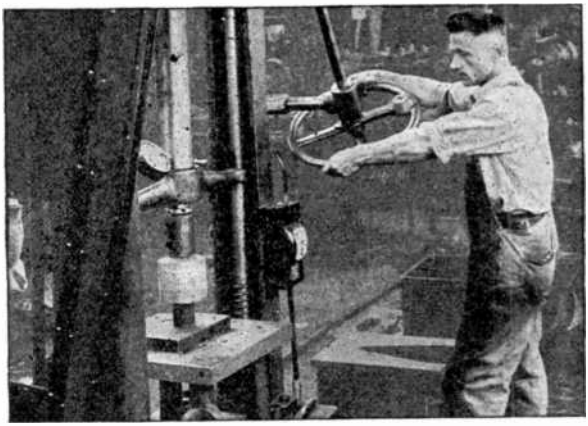


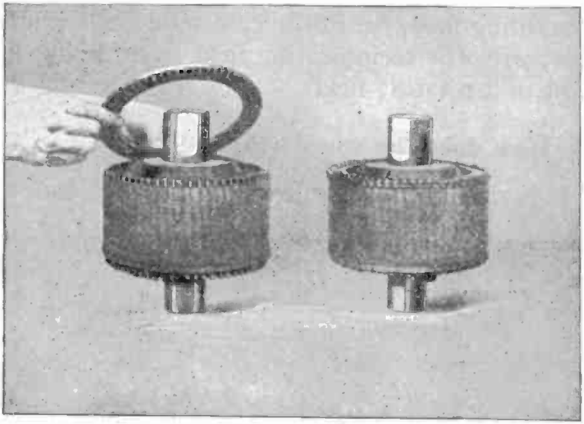
FIG. 2,542.—***Reliance induction motor construction 9.*** Armature laminations are assembled under 5 tons pressure.

"field speed," that is, than "synchronism" or the "synchronous speed."

Ques. What is the difference of speed called?

Ans. The *slip*.

This is a vital factor in the operation of an induction motor, since *there must be slip in order that the armature inductors shall cut magnetic lines* to *induce* (hence the name "*induction*" motor) currents therein so as to create a driving torque.



FIGS. 2,543 and 2,544.—*Reliance induction motor construction 10.* Fig. 2,543, armature with punched copper end ring ready to be placed over extension of bars; fig. 2,544, armature ready for electric welding of bars to end rings.

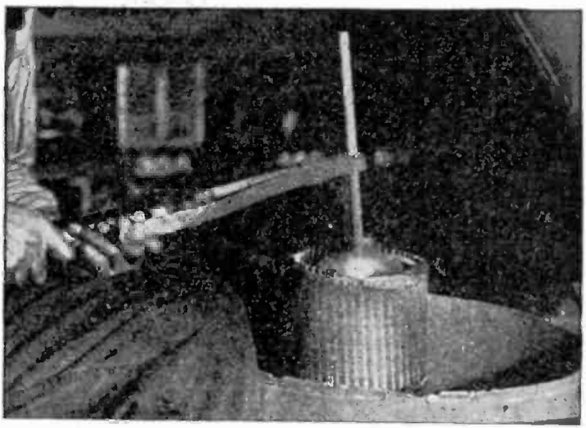


FIG. 2,545.—*Reliance induction motor construction 11.* Welding operation. Bars and end ring are welded into one solid mass to prevent loose connections.

Ques. What is the extent of the slip?

Ans. It varies from about 2 to 5 per cent. of synchronous speed depending upon the size.

Ques. Why are induction motors sometimes called constant speed motors?

Ans. They are erroneously and ill advisedly, yet conveniently so called by builders to distinguish them from induction

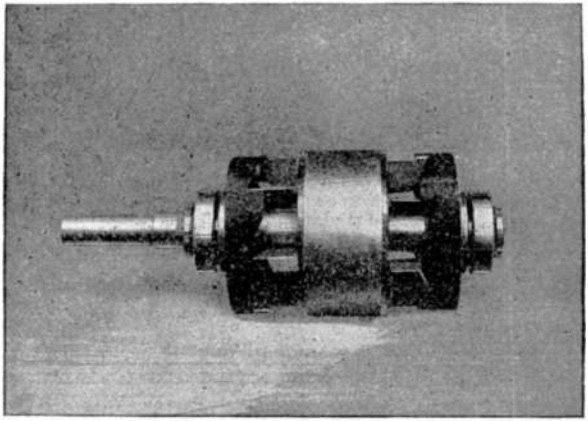


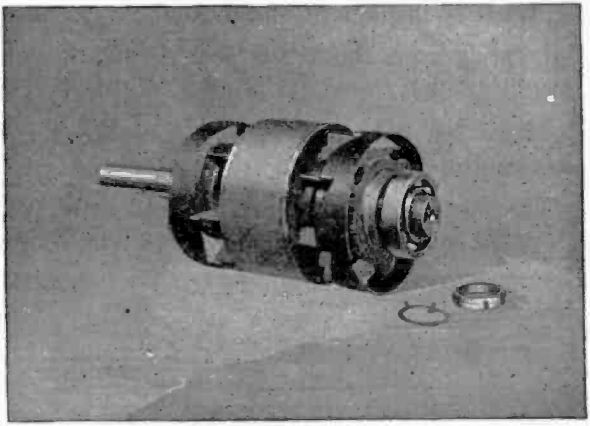
FIG. 2,546.—*Reliance induction motor construction 12.* Completed armature with shaft and ball bearings. The surface of the armature is ground to size. Blowers at each end are provided for ventilation.

motors which are fitted with special devices to obtain widely varying speeds, and which are known as *variable speed* induction motors.

The term *adjustable* would be better.

Motor, Constant Speed.—A motor in which the speed is either constant or does not materially vary; such as synchronous motors, induction motors with small slip, and ordinary direct current shunt motors.—Paragraph 46 of 1907 Standardization Rules of the A. I. E. E.

Motor, Variable Speed.—A motor in which provision is made for varying the speed as desired. The A. I. E. E. has unfortunately introduced the term *varying speed motor,* to designate "motors in which the speed varies with the load, decreasing when the load increases,



FIGS. 2,547 to 2,549.—*Reliance induction motor construction 13.* Armature with lock nut and lock washer removed at front end. In replacing a bearing on the shaft it is simply tapped with a light hammer until the inner race is against a shoulder. It is then locked into place by the lock nut and washer.

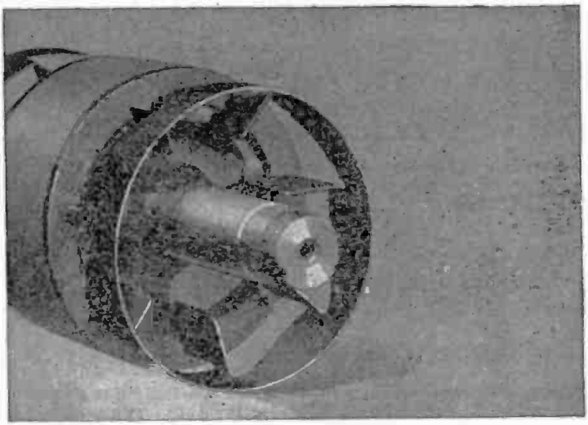


FIG. 2,550.—*Reliance induction motor construction 14.* Blowers are made from one piece of heavy annealed steel. Each individual blade is securely arc welded to the armature so that the blades are held rigid at both ends. The cylindrical shrouds strengthen the blades against centrifugal and axial forces and minimize vibration.

such as series motors." The term is objectionable, since by the expression *variable speed motor* a much more general meaning is intended.

Ques. Why do some writers call the field magnets and armature the primary and secondary, respectively?

Ans. Because, in one sense, the induction motor is a species of transformer, that is, it acts in many respects like a transformer, the primary winding of which is on the field and the secondary winding on the armature.

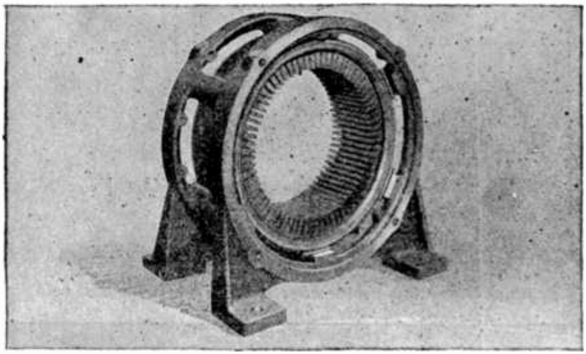


FIG. 2,551.—*Reliance induction motor construction 15.* Skeleton frame with laminations. Open slots are used in the field punchings.

In the motor the function of the secondary circuit is to furnish energy to produce a torque, instead of producing light and heat as in the case of the transformer. Such comparisons are ill advised when made for the purpose of supplying names for motor parts. *There can be no confusion by employing the simple terms armature and field magnets, remembering that the latter is *that part that produces the reciprocating or rotating field* (according as the motor is single or polyphase), and the former, *that part in which currents are induced.*

Ques. Why are polyphase induction motors usually presented in text books before single phase motors?

*NOTE.—*It should be noted* that in some types of motor the function of the two parts are not well defined and where there is any chance of misunderstanding, the terms *stator* and *rotor* should be used. *For instance,* the rotor of a self-starting synchronous motor acts as an *armature* in starting (currents being induced in the squirrel cage bars), and as a *field* in running when the exciting current is turned on.

Ans. Because the latter must start with a substitute for a rotating field and come up to speed before the reciprocating field can be employed.

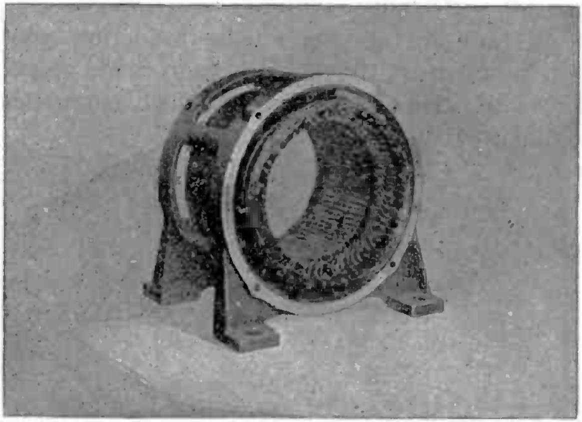


FIG. 2,552.—***Reliance induction motor construction 16.*** Completed field with windings.

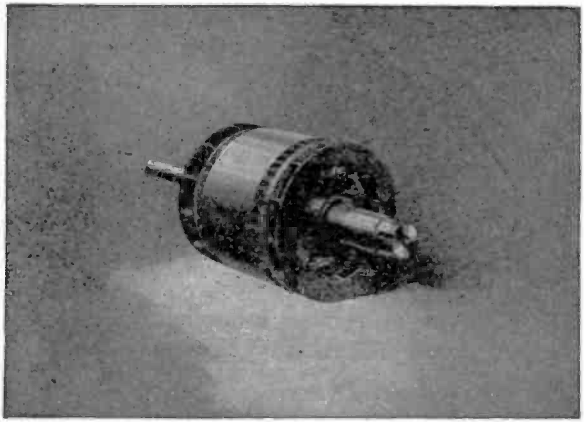


FIG. 2,553.—***Reliance induction motor construction 17.*** Completed field with shaft. Laminations are mounted on cast iron spider. Shafts can be easily removed.

A knowledge then of the production of a rotating field is necessary to understand the action of the single phase motor at starting.

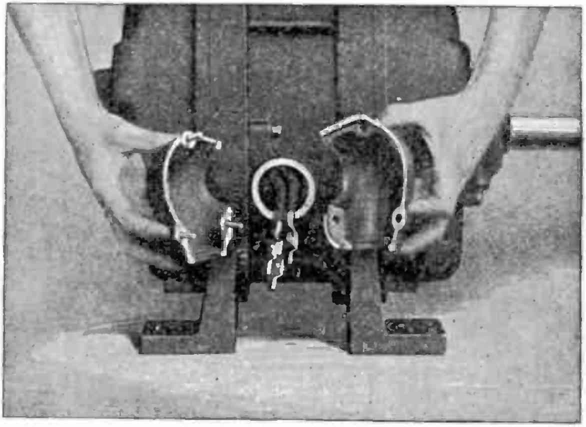


FIG. 2,554.—*Reliance induction motor construction 18.* Removing or replacing outlet for conduit connections. Three accessible screws hold the two halves together.

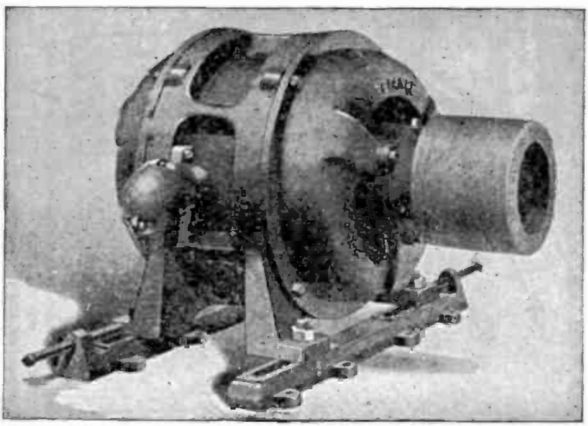


FIG. 2,555.—*Reliance induction motor construction 19.* Motor complete with slide rails and pulley.

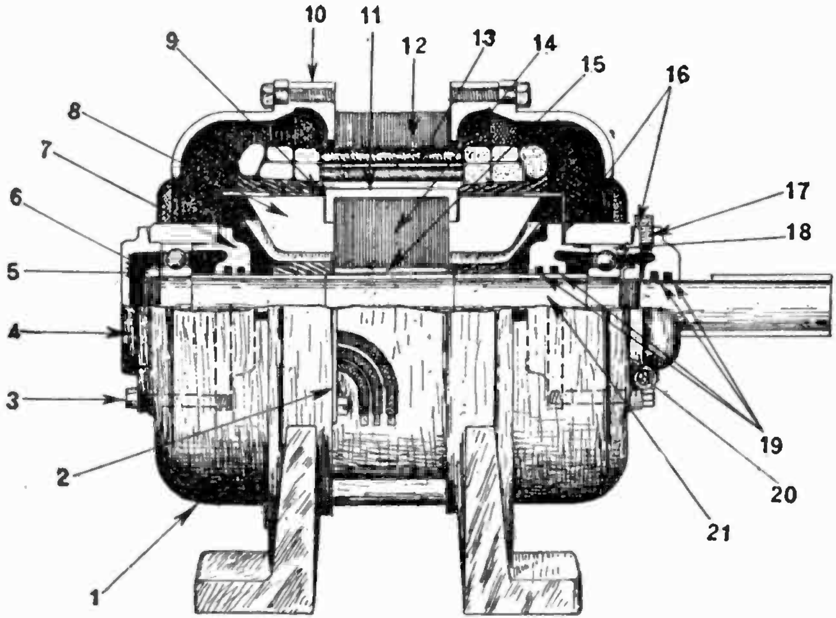


FIG. 2,556.—Sectional view of Reliance type AA ball bearing squirrel cage motor, riveted frame. A special feature of the squirrel cage armature construction is the multiplicity of short circuiting rings. The holes in the rings are bored slightly smaller than the diameter of the copper rods, and the forced fit gives good contact. The rings having been forced in place are dip soldered in an alloy of tin of high melting point. *The parts are:* 1, bearing bracket; 2, terminal board; 3, bearing assembly screw; 4, outer bearing cap; 5, lock nut; 6, lock washer; 7, inner bearing cap; 8, fan; 9, arc welded short circuiting ring; 10, field and flange; 11, armature bar; 12, field laminations; 13, field coils; 14, armature laminations; 15, armature key; 16, vellumoid gaskets; 17, filling plug; 18, ball bearing assembly; 19, felt grease seals; 20, drain plug; 21, shaft; 22, complete field; 23, armature; 24, slide rails.

Polyphase Induction Motors.—As many central stations put out only alternating current circuits, it has become necessary for motor builders to perfect types of alternating current motor suitable for all classes of industrial drive and which are adapted for use on these commercial circuits.

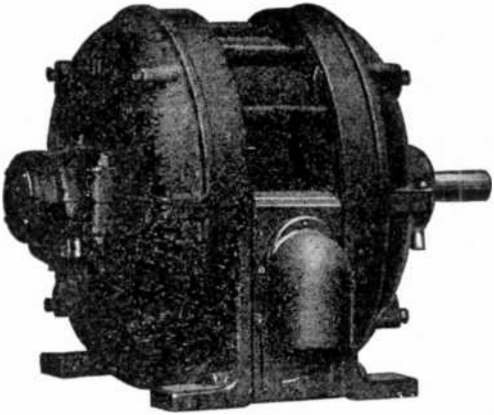


FIG. 2,557 —Allis Chalmers type AR squirrel cage polyphase motor with split housings for direct connection.

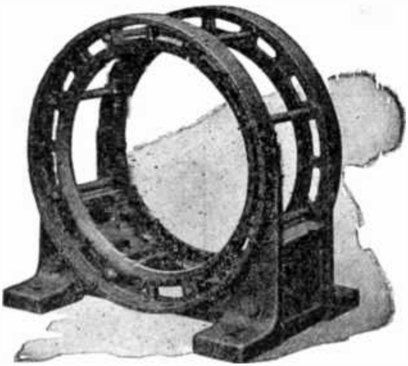


FIG. 2,558.—Allis Chalmers skeleton cast steel frame for type A.R. motor showing saddle blocks.

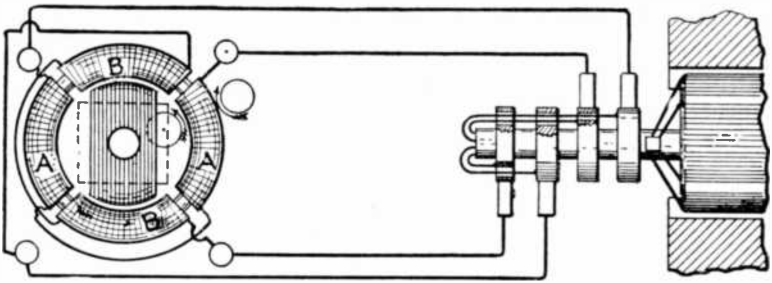


FIG. 2,559.—Tesla's rotating magnetic field. The figure is from one of Tesla's papers as given in *The Electrician*, illustrating how a rotating magnetic field may be produced with stationary magnets and polyphase currents. *The illustration shows* a laminated iron ring overwound with four separate coils, A,A and B,B, each occupying about 90° of the periphery. The opposite pairs of coils A,A and B,B, respectively are connected in series and joined to the leads from a two phase alternator, the pair of coils A,A, being on one circuit and the coils B,B, on the other. The resultant flux may be obtained by combining the two fluxes due to coils A,A and B,B, taking account of the phase difference of the two phase current, as in fig. 2,560.

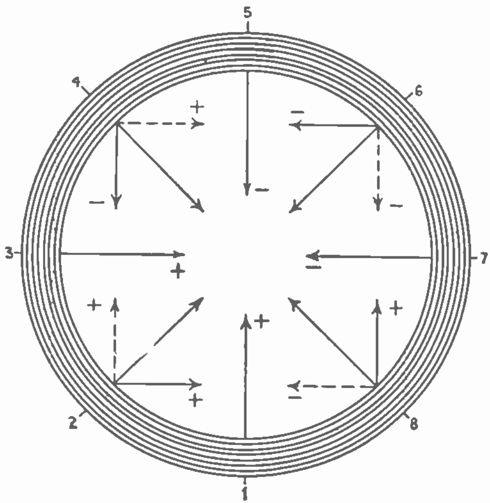


FIG. 2,560.—Method of obtaining resultant flux of Tesla's rotating magnetic field. The eight small diagrams here seen show the two components and resultant for eight equivalent successive instants of time during one cycle. At 1, the vertical flux is at + maximum and

In regard to polyphase motors it should be noted that for given requirements of load and voltage, the amount of copper required in the distributing system is less. On account of the saving in copper three phase motors are preferal le to two phase wherever service conditions will permit.

The construction of an induction motor is very simple, and since there are no sliding contacts as with commutator motors, there can be no sparks during operation—a feature which adapts the motor for use in places where fire hazards are prominent.

The motor consists, as already mentioned, simply of two parts: *an armature and field magnets, without any electrical connection between these parts.* Its operation depends upon:

1. *The production of a rotating magnetic field;*

2. *Induction of eddy currents in the armature;*

3. *Reaction between the rotating magnetic field and the eddy currents.*

FIG. 2,560.—*Text continued.*

the horizontal is zero. At 2, the vertical flux is still + but decreasing, and the horizontal is + and increasing, the resultant is the thick line sloping at 45° upward to the right. At 3, the vertical flux is zero, and the horizontal is at its + maximum, and similarly for the other diagrams. Thus at 8, the vertical flux is + and increasing, while the horizontal is − and decreasing, the resultant is the thick line sloping at 45° upward to the left. At points 2, 4, 6, and 8 the increasing fluxes are denoted by full, and the decreasing by dotted lines. The laminated iron of the ring is indicated by the circles, and the result is that at the instants chosen the flux across the plane of the ring is directed inward from the points 1, 2, 3, 4, etc., on the inner periphery of the iron. There will, therefore, appear successively at these points effective north poles, the corresponding south poles being simultaneously developed at the points diametrically opposite. These poles travel continuously from one position to the next, and thus the magnetic flux across the plane of the ring swings round and round, completing a revolution without change of intensity during the cycle time of the current.

Production of a Rotating Magnetic Field.—It should at once be understood that the term "rotating field" does not signify that part of the apparatus revolves, the expression merely refers to the magnetic lines of force set up by the field magnets without regard to whether the latter be the stationary or rotating member.

A rotating magnetic field may be defined as *the resultant magnetic field produced by a system of coils symmetrically placed and supplied with polyphase currents.*

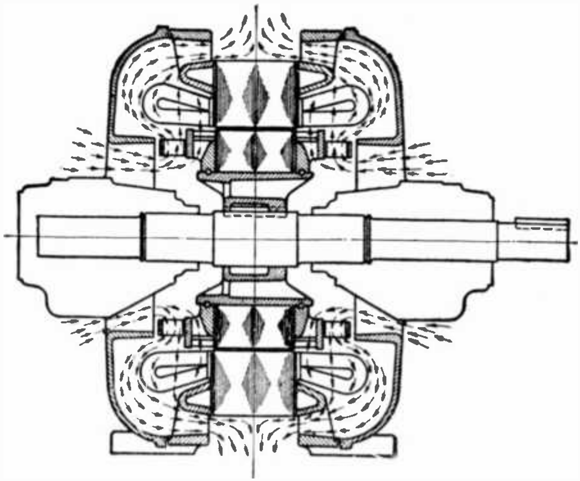


FIG. 2,561.—Ventilation diagram of Allis Chalmers AR squirrel cage polyphase motor. The ventilation is secured by air being drawn in through openings around the bearing hubs of the housings by means of shrouded fans supported by the armature. Passing through the fans, the air is blown around the ends of the field coils and discharged through openings in the cast steel end frames across the back of the laminations in a direction parallel to the shaft. This method of discharge eliminates the possibility of dust and dirt dropping into the air passages and retarding the ventilation of the machine.

A rotating magnetic field can, of course, be produced by spinning a horse shoe magnet around its longitudinal axis, but with polyphase currents, as will be later shown, the rotation of the field can be produced without any movement of the mechanical parts of the electro-magnets.

The original rotating magnetic field dates back to 1823, when Francois Jean Arago, an assistant in Davy's laboratory, discovered that if a magnet be rotated before a metal disc, the latter had a tendency to follow the motion of the magnet, as here shown in fig. 2,562 and explained in fig. 2,563. This experiment led up to the discovery which was made by Arago in 1824, when he observed that the *number of oscillations which a magnetized needle makes in a given time, under the influence of the earth's magnetism, is very much lessened by the proximity of certain metallic masses*, and especially of copper, which may reduce the number in a given time from 300 to 4.

The explanation of Arago's rotations is that *the magnetic field cutting the disc produces eddy currents therein and the reaction between the latter and the field causes the disc to follow the rotations of the field.*

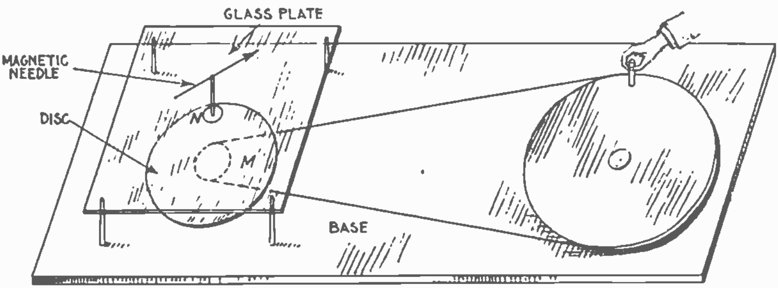


FIG. 2,562.—Arago's rotations. The apparatus necessary to make the experiment consists of a copper disc M, arranged to rotate around a vertical axis and operated by belt drive, as shown. By turning the large pulley by hand, the disc M, may be rotated with great rapidity. Above the disc is a glass plate on which is a small pivot supporting a magnetic needle N. If the disc now be rotated with a slow and uniform velocity, the needle is deflected in the direction of the motion, and stops at an angle of from 20° to 30° with the direction of the magnetic meridian, according to the velocity of the rotation of the disc. If the velocity increase, the needle is ultimately deflected more than 90° and then continues to follow the motion of the disc.

The induction motor is a logical development of the experiment of Arago, which so interested Faraday while an assistant in Davy's laboratory and which led him to the discovery of the laws of electro-magnetic induction, which are given in Chapter X.

*In 1885, Professor **Ferraris,** of Turin, **discovered** that *a rotating field could be produced from stationary coils by means of polyphase currents.*

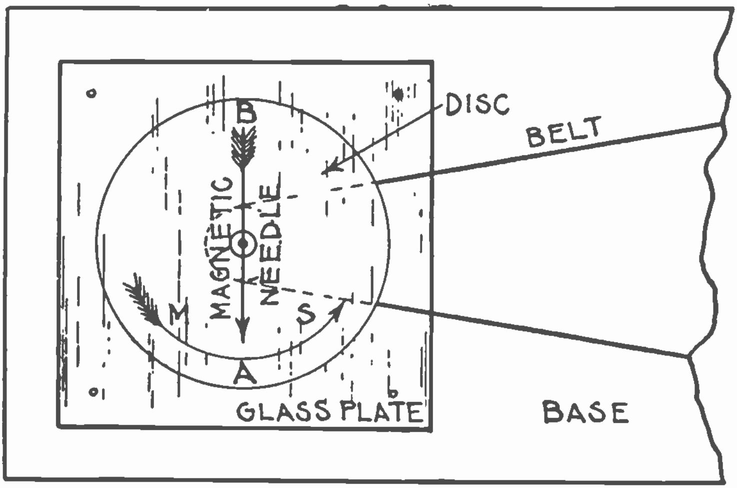


FIG. 2,563.—Explanation of Arago's rotations. Part of fig. 2,562 is here reproduced in plan. Faraday was the first to give an explanation of the phenomena of magnetism by rotation in attributing it to the induction of currents which by their electro-dynamic action, oppose the motion producing them; the action is mechanically analogous to friction. In the figure, let AB, be a needle oscillating over a copper disc, and suppose that in one of its oscillations it goes in the direction of the arrow from M, to S. In approaching the point S, for instance, it develops there a current in the opposite direction, and which therefore repels it; in moving away from M, it produces currents which are of the same kind, and which therefore attract, and both these actions concur in bringing it to rest. Again, suppose the metallic mass turn from M, toward S, and that the magnet be fixed; the magnet will repel by induction points such as M, which are approaching A, and will attract S, which is moving away; hence the motion of the metal stops, as in Faraday's experiment. If in Arago's experiment the disc be moving from M, to S, M, approaches A, and repels it, while S, moving away, attracts it; hence the needle moves in the same direction as the disc. If this explanation be true, all circumstances which favor induction will increase the dynamic action; and those which diminish the former will also lessen the latter.

*NOTE.—Walmsley attributes the first production of rotating fields to Walter Bailey in 1879, who exhibited a nodel at a meeting of the Physical Society of London, but very little was done, it is stated, until Ferraris took up the subject.

*This discovery was commercially applied a few years later by Tesla, Brown, and Dobrowolsky.

The principles of polyphase motors can be best understood by means of elementary diagrams illustrating the action of polyphase currents in producing a rotating magnetic field, as explained in the paragraphs following.

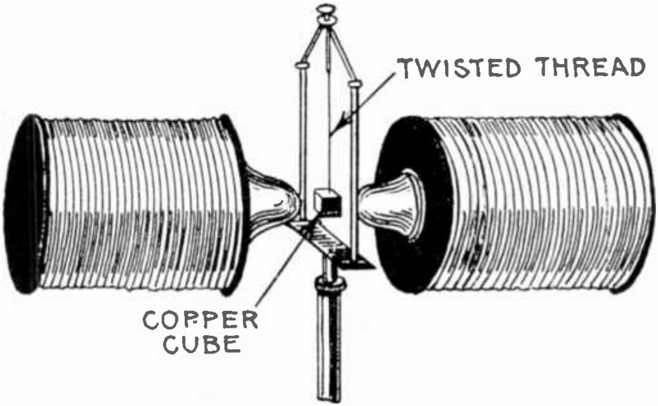


Fig. 2,564.—Experiment made by Faraday being the reverse of Arago s first observation. Faraday assumed that since the presence of a metal at rest stops the oscillations of a magnetic needle, the neighborhood of a magnet at rest ought to stop the motion of a rotating mass of metal. He suspended a cube of copper by a twisted thread, which was placed between the poles of a powerful electro-magnet. When the thread was left to itself, it began to spin round with great velocity, but stopped the moment a powerful current was passed through the electro-magnet.

Production of a Rotating Magnetic Field by Two Phase Currents.—Fig. 2,565 represents an iron ring wound with coils of insulated wire, which are supplied with a two phase current at the four points A′, A″, B′, B″, the points A′ and A″, and B′ and B″, being electrically connected.

According to the principles of electro-magnetic induction, if only one

*NOTE.—*The Tesla patents* were acquired in the U. S. by the Westinghouse Co. in 1888, and polyphase induction motors, as they were called, were soon on the market. Brown of the Oerlikon Machine Works developed the single phase system and operated a transmission plant over five miles in length at Kassel, Germany, which operated at 2,000 volts.

current A, entered the ring at A′, and the direction of the winding be suitable, a negative pole (—) will be produced at A′, and a positive (+) at A″, so that a magnetic needle pivoted in the center of the ring would tend to point vertically upward toward A′.

Now suppose that at this instant, corresponding to the beginning of an alternating current cycle, a second current B, differing in phase from the first by 90 degrees, be allowed to enter the ring at B″.

Accordingly, as shown in the figure when the pressure of the current A, is at its maximum, that of the current B, is at its minimum; therefore even with a two phase current, at the beginning of the cycle, the needle will point toward A′.

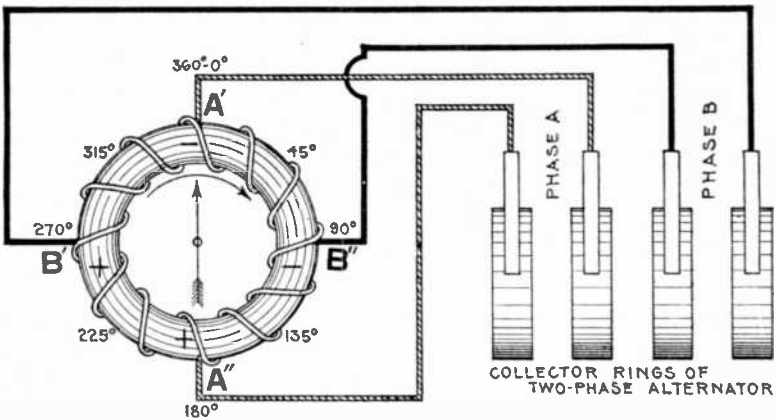


FIG. 2,565.—Production of a rotating magnetic field by two phase currents. The figure represents an iron ring, wound with coils of insulated wire, and supplied with two phase currents at the four points A, B, C, and D. The action of the two phase current on the ring in producing a rotating magnetic field is explained in the accompanying text.

As the cycle continues, however, the strength of A, will diminish and that of B, increase, thus shifting the induced pole toward B″, until B, attains its maximum and A, falls to its minimum at 90° or the end of the first quarter of the cycle, when the needle will point toward B″.

At 90° the phase of A, current reverses in direction and produces a negative pole at A″, and as its strength increases from 90° to the 180° point of the cycle, and that of phase B, diminishes, the resultant negative pole is shifted past B″, toward A″, until A, attains its maximum and B, falls to its minimum at 180° and the needle points in the direction of B″.

At the 180° point of the cycle, B, reverses in direction and produces a negative pole at B′, and as the fluctuation of the pressure of the two currents during the second half of the cycle, from 180° to 360°, bear the same relation to each other as during the first half, the resultant poles of the rotating magnetic field thus produced carry the needle around in continuous rotation so long as the two phase current traverses the windings of the ring.

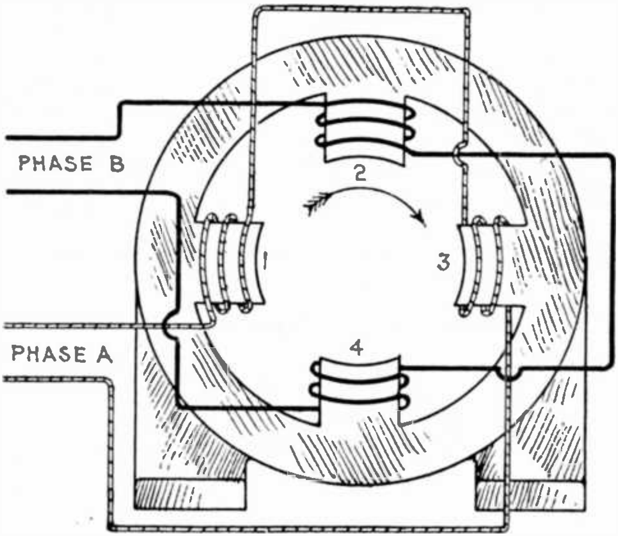
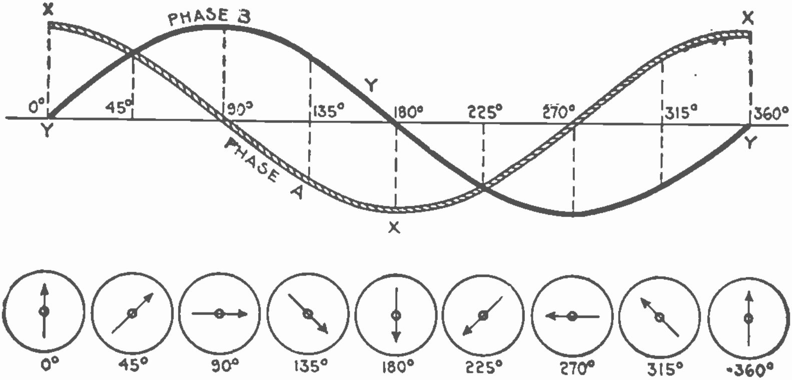


FIG. 2,566.—Production of rotating magnetic field in a two pole two phase motor. The poles are numbered from 1 to 4 in a clockwise direction. Phase A winding is around poles 1 and 3, and phase B winding, around poles 2 and 4. In each case the poles are wound alternately, that is, if 1 be wound clockwise, 3 will be wound counter clockwise, thus producing unlike polarity in opposite poles. Now during one cycle of the two phase current, the following changes take place, starting with pole 1, of N polarity and 3, of S polarity.

	One Cycle			
Degrees	0° to 90°	90° to 180°	180 to 270°	270° to 360°
Polarity	1N – 3S	2N – 4S	3N – 1S	4N – 2S



FIGS. 2,567 to 2,576.—Diagram showing resultant poles due to two phase current.

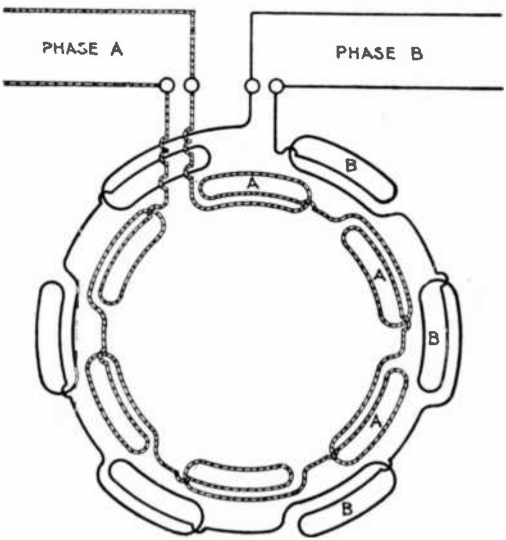


FIG. 2,577.—Diagram of two phase, six pole field winding. There are six coils in each phase as shown. The coils of each phase are connected in series, adjacent coils being joined in opposite senses, thus, for each phase, first one coil is wound clockwise, and the next counter clockwise.

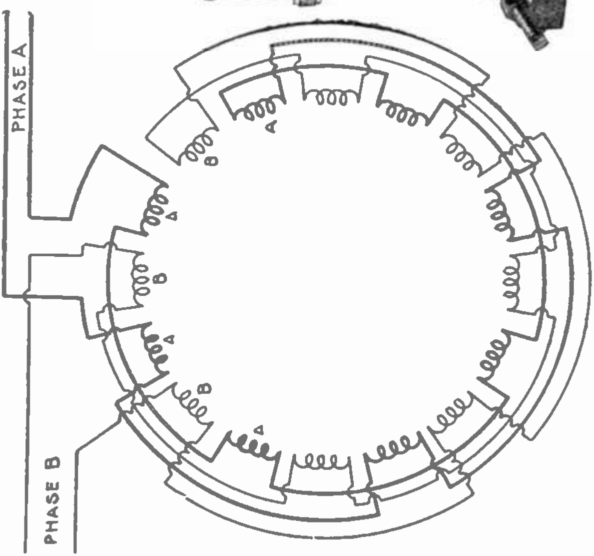


FIG. 2,578.—Diagram of two phase, eight pole field winding. The winding is divided into 16 groups (equal to the product of the number of poles multiplied by the number of phases). Each group such as at A, comprises a number of coils in series, each coil being located in a separate pair of slots, the end of one being connected to the beginning of the next. When the currents are in the same direction, the currents circulate in the same direction in two adjacent groups, a pole then with this arrangement being formed by two groups, both phases contributing to the formation of the pole. After ½ cycle when the current in each phase reverses, the pole advances the angular distance, covered by two groups; hence the field completes one revolution in eight alternations of current.

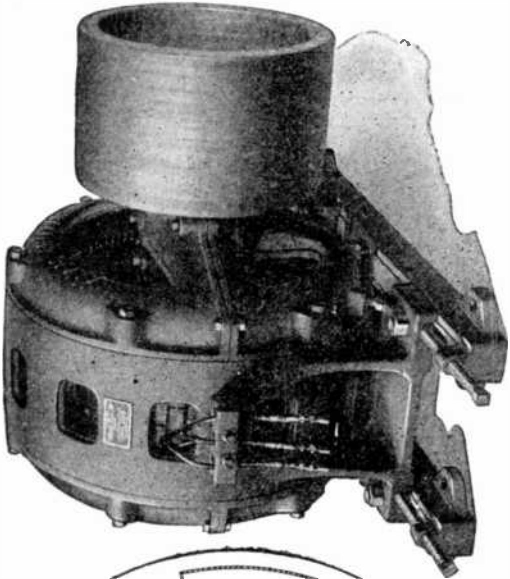
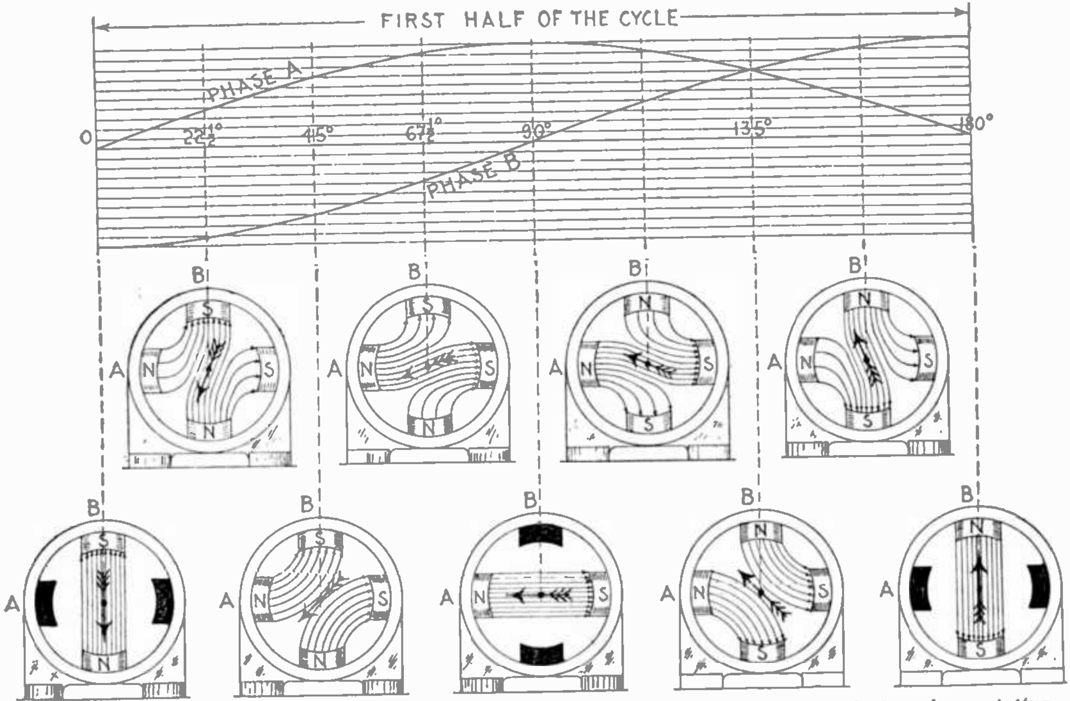
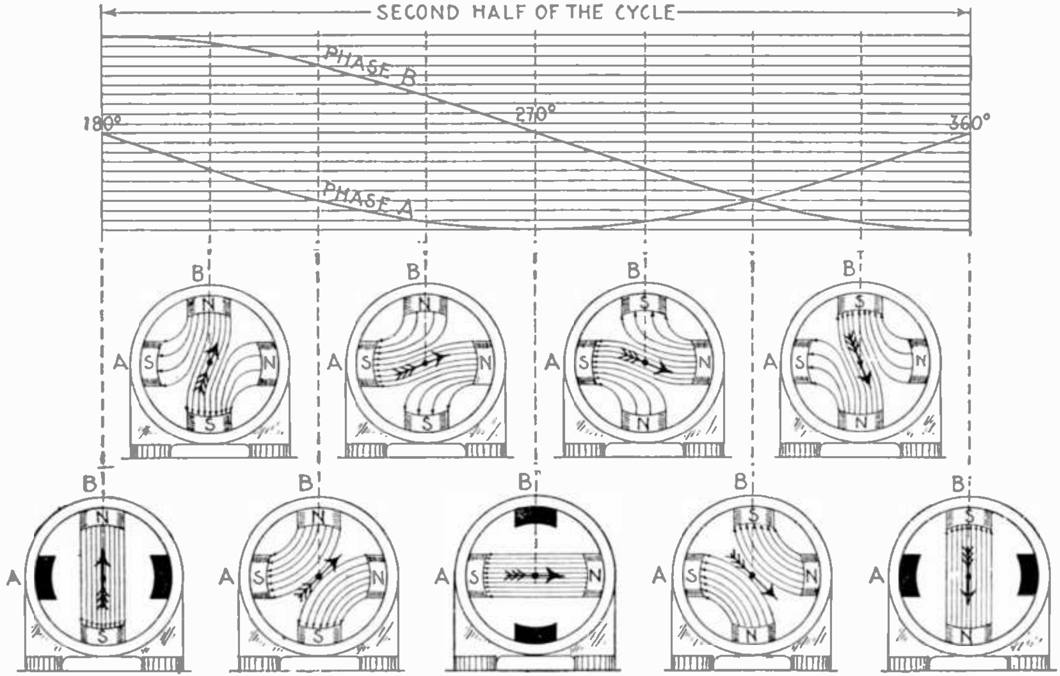


FIG. 2,579.—Allis Chalmers 100 *h.p.* 690 *r.p.m.* belted squirrel cage motor.



FIGS. 2,580 to 2,599.—Sine curves of two phase current and diagrams showing the physical conception of a ***two phase rotating magnetic field.*** The alternating magnetizing current is assumed to be of such strength that, at its maximum strength, the field produced may be represented by 10 lines of force as indicated by the parallel lines. At the beginning of the rotation, fig. 2,580, phase A magnetization, according to sine curve is zero, indicated by the solid black poles, while phase B is of strength 10 with



FIGS. 2,580 to 2,599.—*Text continued.*
current in the direction to produce a south pole at B. Similarly, in fig. 2,531, the strength of A is 4 lines, and of B, 9 lines, the resultant magnetization having rotated $22\frac{1}{2}°$. The direction of the resultant magnetization is indicated by the arrow in each figure. It should be noted in fig. 2,586, that the polarity of B is reversed, the current curve now being above the zero line. By following the arrow through the successive positions the rotation of the resultant magnetization is clearly seen.

Production of Rotating Magnetic Field by Three Phase Current.—A rotating magnetic field is produced by the action of a three phase current in a manner quite similar to the action of a two phase current. Fig. 2,601 shows a ring suitably wound and supplied with a three phase current at three points A, B, C, 120° of a cycle apart.

At the instant when the current *a*, flowing in at A, is at its maximum, two currents *b* and *c*, each one-half the value of *a*, will flow out B and C,

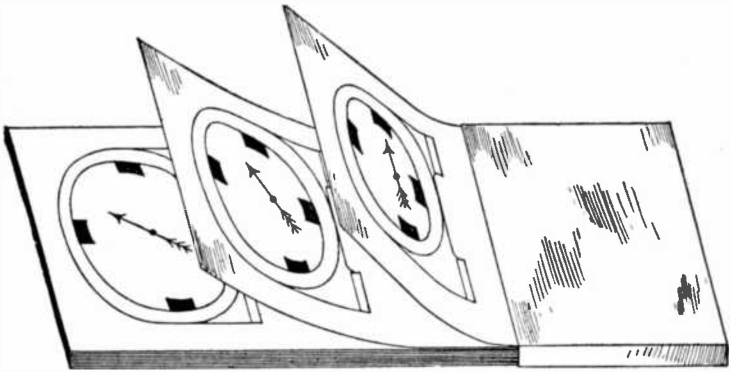


Fig. 2,600.—Moving picture method of showing motion of a rotating magnetic field. A number of sheets of paper are prepared, each containing a drawing of the motor frame and a magnetic needle in successively advancing angular positions, indicating resultant directions of the magnetism. The sheets are bound together so that the axis of the needle on each sheet coincides. When passing the sheets in one way the revolving field will be seen to rotate in one direction, while, when moving the sheets backward, the rotation of the magnetic field is in the opposite direction, showing that the reversal of the order of the coils has the effect of reversing the rotation of the magnetic field.

thus producing a negative pole at A, and a positive pole at B, and at C. The resultant of the latter will be a positive pole at E, and consequently, the magnetic needle will point toward A.

As the cycle advances, however, the mutual relations of the fluctuations of the pressures of the three currents, and the time of their reversals of direction will be such, that when a maximum current is flowing at any one of the points A, B, and C, two currents each of one-half the value of the entering current will flow out of the other two points, and when two currents are entering at any two points, a current of maximum value

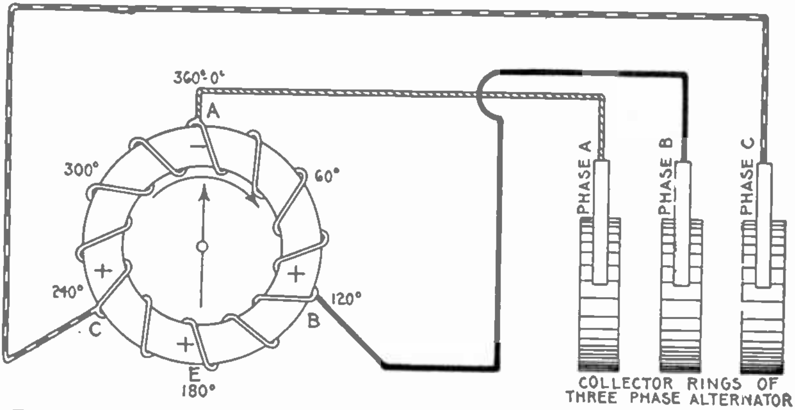


FIG. 2,601.—Production of a rotating magnetic field by three phase current. A ring, wound as shown is tapped at points A, B, and C, 120° apart, and connected with leads to a three phase alternator. As described on page 1,804, a rotating magnetic field is produced in a manner similar to the two phase method.

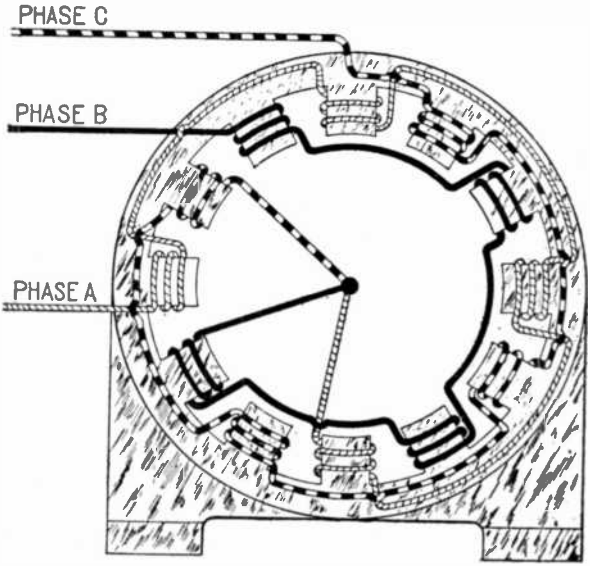


FIG. 2,602.—Diagram of three phase, four pole Y connected field winding.

will flow out of the other point. This action will produce one complete rotation of the magnetic field during each cycle of the current.

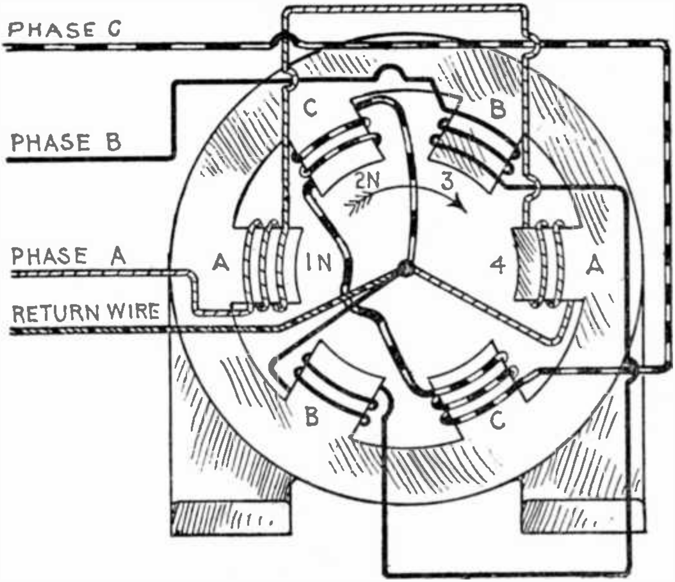


FIG. 2,603.—Production of a rotating magnetic field in a two pole three phase motor. In order to obtain a uniformly rotating magnetic field, it is necessary to arrange the phase windings in the direction of rotation, in the sequence ACB, not ABC, as indicated on the magnets. Thus poles 1 and 4 are connected in series to phase A, 2 and 5 in series to phase C, and 3 and 6 in series to phase B. The different phase windings are differently lined, and it should be noted that they have a common return wire, though this is not absolutely necessary. Since the phases of the three currents differ from each other by one-third of a period or cycle, each of the phase windings will therefore set up a field between its poles, which at any instant will differ, both in direction and magnitude, from the fields set up by the other phase windings. Hence, the three phase windings acting together will produce a resultant field, and if plotted out, the directions of this field for various fractions of the period is such that in one complete period the resultant field will make one complete round of the poles in a clockwise direction, as indicated by the curved arrow. The positions of the resultant field during one complete period may be tabulated as follows:

	One Cycle					
	0° to 60°	60° to 120°	120° to 180°	180° to 240°	240° to 300°	300° to 360°
Polarity	1N – 4S	2N – 5S	3N – 6S	4N 1S	5N – 2S	6N – 3S

Formation of Magnetic Poles in the Armature.—A copper cylinder placed in a rotating magnetic field will turn in the same direction as the rotation of the field.

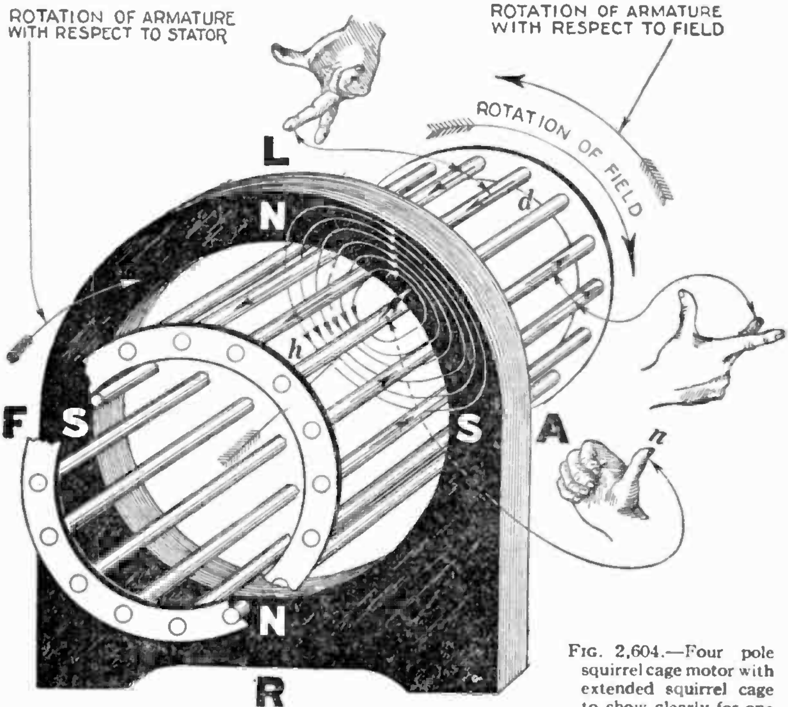
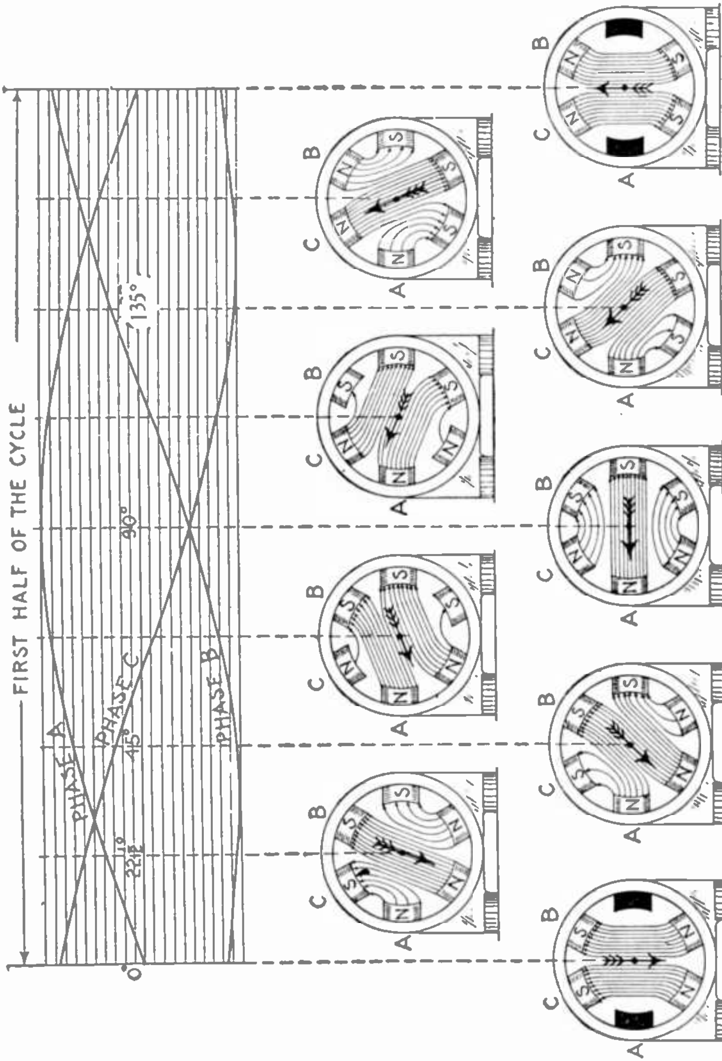
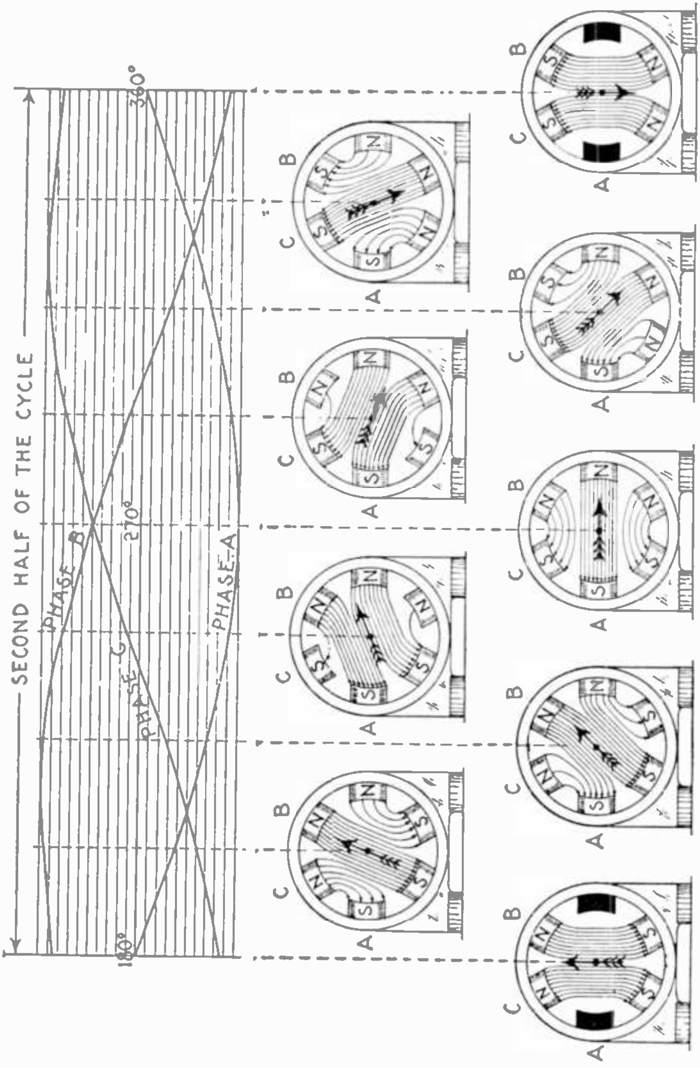


FIG. 2,604.—Four pole squirrel cage motor with extended squirrel cage to show clearly for one quadrant magnetic field distribution and induced polarization of the squirrel cage. *At any instant* there is a maximum field density at four points in the stator, as at **L**, **A**, **R**, **F**, for the instant here shown, there being north poles at **L**, and **R**, and south poles at **A**, and **F**. With clockwise field rotation, currents will be induced in the squirrel cage as shown, resulting in a north pole through bar *hd*. This produces the torque both by repulsion and attraction, tending to rotate the squirrel cage clockwise.

NOTE.—*Speed and torque relation.* When an induction motor is running at zero load, but little torque is required to drive it, and the armature revolves at a speed but very little less than that of the rotating field (the speed of the rotating magnetic field is called the synchronous speed). When the motor is running with a load, the driving torque must be large, and therefore the current in the armature inductors must be large in order that the armature magnetism may exert the necessary driving force upon the armature inductors; furthermore the induced voltage in the armature inductors must be sufficient to produce the necessary armature currents, and to do this the armature must run appreciably below synchronism.



FIGS. 2,605 to 2,624.—Sine curves of three phase current and diagrams showing the physical conception of a ***three phase rotating magnetic field***. The diagrams are constructed in the same manner as explained in figs. 2,580 to 2,599. It should be noted that the phase windings are arranged in the direction of rotation in the sequence ACB, phase C, being wound in opposite



FIGS. 2,605 to 2,624.—*Text continued.*
sense to A and B, as indicated by the curve, in that north poles are produced at A and B, when the respective curves are above the zero line, a south pole being produced at C, when its curve is above the zero line. The rotation of the resultant magnetization is clearly seen by following the arrow through its successive positions.

The torque tending to turn the cylinder is due to the induction of eddy currents which produce unlike poles at the center of the whirls, as shown in fig. 2,626.

For simplicity, the rotating magnetic field may be supposed to be produced by a pair of magnetic poles placed at opposite sides of the cylinder and *revolved around it* as in fig. 2,626.

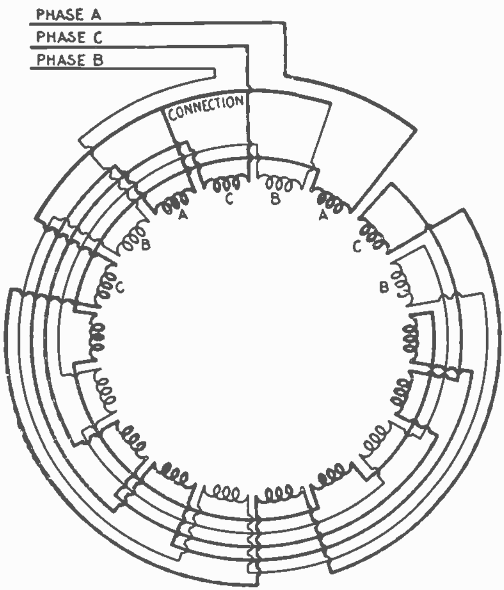


FIG. 2,625.—Diagram of three phase, six pole field winding. There are 18 groups, and the sequence of phases is ABC, in a counter clockwise direction. For a Y connection, the middle phase is reversed, so that a pole will be formed by the three consecutive phases when the current is in the same direction in A and C, and opposite in B. The beginning of the middle coil C, and not the end, as with the other two, is connected to the common point O. In this case the pole shifts a distance equal to three groups for each alternation, so that one revolution of the field requires three cycles.

Now, for instance, in starting, the cylinder being at rest any element or section of the surface as the shaded area A B, will, as it comes into the magnetic field of the rotating magnet, cut magnetic lines of force inducing a current therein, whose direction is easily determined by applying Fleming's rule.

Since the field is not uniform, but gradually weakens, as shown, on either side of the shaded area (which is just passing the center), the pressure induced on either side will be less

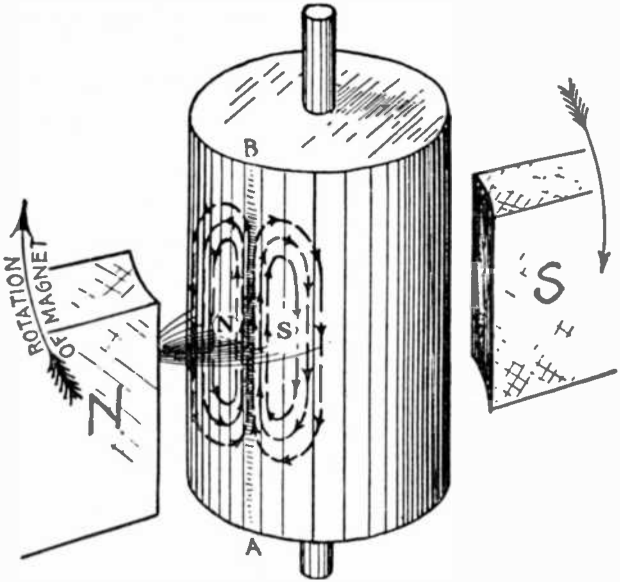


FIG. 2,626.—Copper cylinder and rotating magnet *illustrating the principle of operation of an induction motor*. The "rotating magnetic field" which is necessary for induction motor operation is for simplicity here produced by rotating a magnet as shown. ***In starting***, the cylinder being at rest, any element as AB, as it is swept by the field will cut magnetic lines, which will induce a current upward in direction as determined by applying Fleming's rule (as given on page 133). The inductive action is strongest at the center of the field hence as AB, passes the center the induced pressure along AB, is greater than along elements more or less remote on either side. Accordingly a pair of eddy currents will result as shown (see fig. 716, page 497). Applying the right hand rule for polarity of these eddy currents (see fig. 286, page 185) it will be seen that a S pole is induced by the eddy on the side of the cylinder receding from the magnet, and a N pole by the eddy on the side toward which the magnet is approaching. The cylinder, then, is *attracted* in the direction of rotation of the magnet by the induced pole on the receding side, and *repelled* in the same direction by the induced pole on the approaching side. Accordingly, the cylinder begins to rotate. The velocity with which it turns depends upon the load; it must always turn *slower* than the magnet, in order that its elements may cut magnetic lines and induce poles to produce the necessary torque to balance the load. The difference in speed of the magnet and cylinder is called the *slip*. Evidently the greater the load, the greater is the slip required to induce poles of sufficient strength to maintain equilibrium. The figure is drawn somewhat distorted, so that both eddies are visible.

than that induced in the shaded area, giving rise to eddy currents (as illustrated in fig. 2,628, page 1,813). These eddy currents induce poles as indicated at the centers of the whirls, the polarity being determined by applying the right hand rule as shown in fig. 286, page 185).

By inspection of fig. 2,626, it is seen that *the induced pole toward which the magnet is moving is of the same polarity as the*

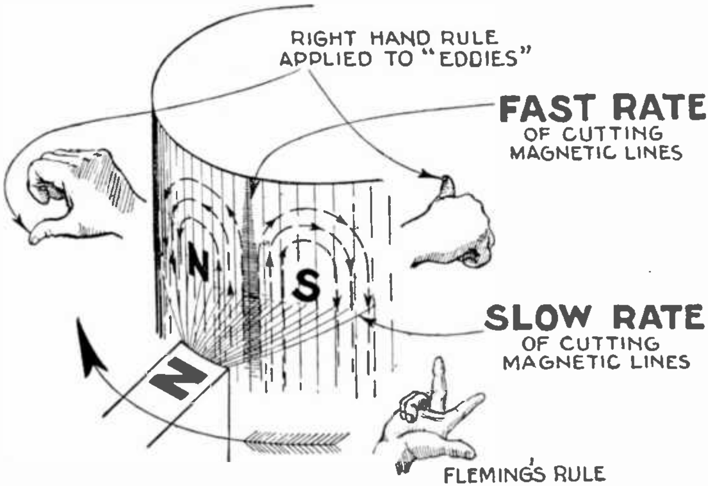


FIG. 2,627.—Detail of elementary copper cylinder and rotating magnet showing the variable rate of cutting *magnetic lines* which gives rise to eddy currents and resulting N and S poles.

magnet; therefore it is **repelled,** *while the induced pole from which the magnet is receding, being of opposite polarity, is* **attracted.** *A torque is thus produced tending to rotate the cylinder.*

NOTE.—*In order to avoid confusion* in applying Fleming's rule, it may be well to regard the pole as being stationary and the cylinder as in motion; for, since motion is "purely a relative matter" (see page. 1,556), the inductive action will be the same as if the pole stood still while the cylinder revolved from left to right, that is, counter clockwise, looking down on it. Regarding it thus (pole stationary and cylinder revolving counter clockwise) Fleming's rule (see fig. 2,627) is easily applied to ascertain the direction of the induced current, which is found to flow upward in the shaded area as shown.

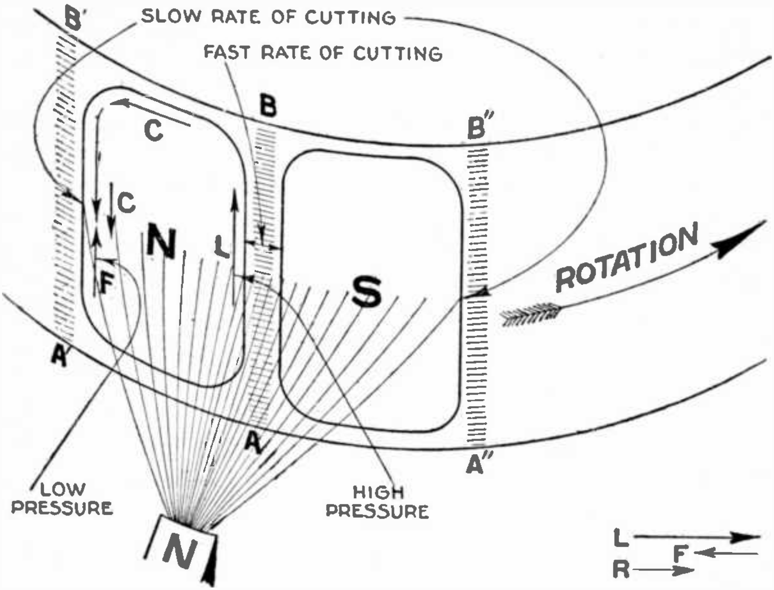


FIG. 2,628.—Detail of copper cylinder armature showing why the variable rate of cutting magnetic lines gives rise to eddy currents. Consider any two elements as AB, and A'B' in dense and weak parts of the field respectively. Evidently AB, will cut the magnetic lines at a high rate and A'B', at a low rate. For simplicity regard the magnet as stationary and the armature rotating to the right as indicated. Now since both elements move across the field in the same direction (applying Fleming's right hand rule) the pressure induced in AB, will be in the same direction as that induced in A'B', as indicated by arrows L and F. Further, since AB, is cutting the magnetic lines faster than A'B', the pressure induced in AB, will be greater than that induced in A'B', as indicated by difference in length of arrows L and F. The result is that the greater pressure L, overcomes the lesser F, giving a small resultant pressure R, which causes current to flow in the direction indicated by arrows C. Similar conditions obtain for elements AB and A''B''.

NOTE.—*The advantages* of the squirrel cage motor over the synchronous motor are lower cost, greater simplicity and the fact that it can be applied where the pull in torque is too great for the synchronous motor. The starting torque on 100% voltage will be approximately 100 to 150% of full load torque, which is within the range of most synchronous motors.

NOTE.—*The squirrel cage* motor as explained in the next chapter can be designed with a high resistance armature to give higher starting torque, but the requirement of lower resistance for good efficiency prevents this except for special cases. For loads requiring high starting torque, and low pull in torque, the synchronous motor has the advantage, as the high resistance armature winding can be used without impairing the efficiency of the synchronous motor. Where the starting torque approaches full load torque and the pull in torque is correspondingly high, there can be little question as to the superiority of the wound armature induction motor over the synchronous motor.

It must be evident that this torque is greatest when the cylinder is at rest, because the magnetic lines are cut by any element on the cylindrical surface at the maximum rate.

Moreover, as the cylinder is set in motion and brought up to speed, the torque is gradually reduced, because the rate with which the magnetic lines are cut is gradually reduced.

Ques. What is the essential condition for the operation of an induction motor?

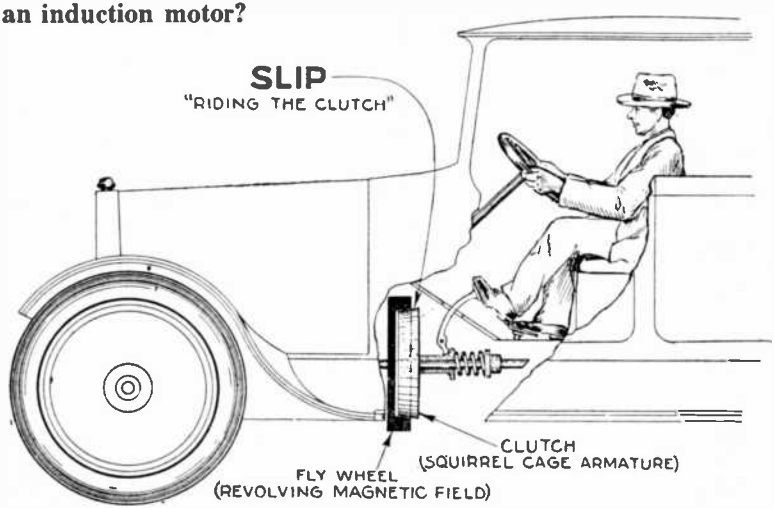


FIG. 2,629.—"Riding the clutch" analogy of *slip*. An automobile driver who either through ignorance or indifference, will sometimes as in traffic try to overcome an inherent fault of the gas engine and obtain very slow speed by *riding the clutch*, that is, reduce the clutch friction by pressure on the clutch pedal until the clutch *slips*. Under such conditions the fly wheel rotates faster than the clutch. *Similarly* in an induction motor the rotating magnetic field, which corresponds to the fly wheel, rotates faster than the clutch. The clutch corresponds to the squirrel cage armature. Slip is necessary for the operation of a squirrel cage motor, but unnecessary for the proper operation of an automobile.

Ans. The armature, or part in which currents are induced, must rotate at a speed slower than that of the rotating magnetic field.

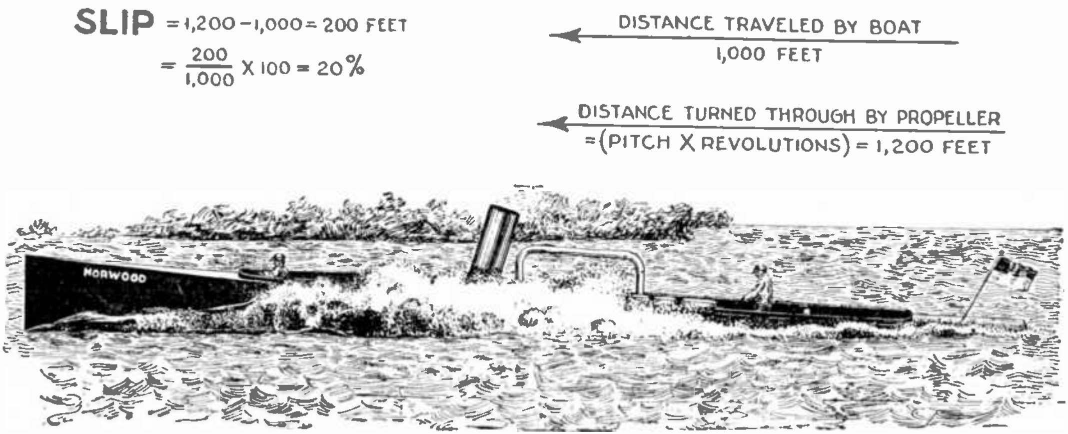


FIG. 2,630.—Marine analogy of slip. ***In operation*** if the screw propeller revolved through an unyielding substance (as a screw turning in a nut) it would propel the boat a distance equal to that turned through by the propeller, that is, equal to the pitch of the propeller multiplied by the revolutions. However, water is not an unyielding substance and there is always more or less slip; that is, the distance turned through by the propeller is always greater than the distance traveled by the boat in any given interval of time; the difference is called the slip. ***Similarly***, in the operation of a squirrel cage motor the speed of the rotating magnetic field is always greater than the speed of the squirrel cage armature, the difference is the slip and is expressed as a percentage of the speed of the rotating magnetic field.

In the elementary induction motor, fig, 2,626, the cylinder is the armature, and the rotating magnets are the equivalent of a rotating magnetic field.

Ques. What is the difference of speed called?

Ans. *The slip.*

Ques. Why is slip necessary in the operation of an induction motor?

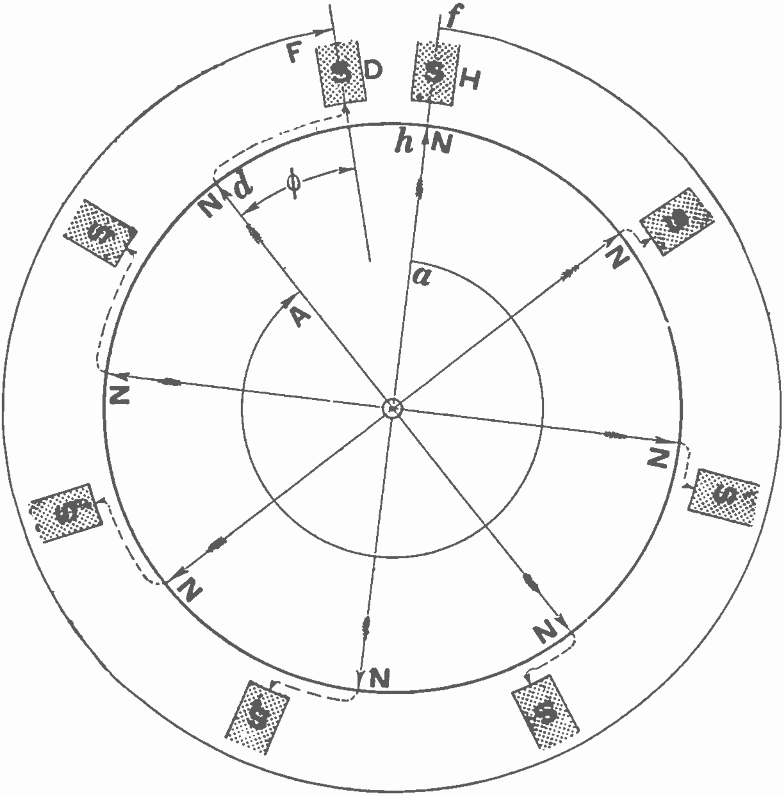
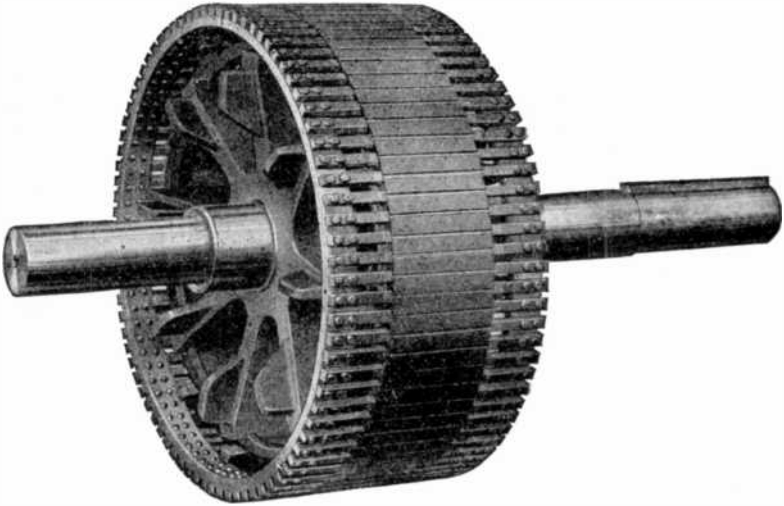


FIG 2,631.—Top view of copper cylinder armature and south pole of rotating magnet illustrating progressively *slip.* *In operation*, assume at a given instant, the element *h*, of the copper cylinder to be opposite the S, pole of rotating magnet at position H. Now, since the magnet is rotating (clockwise) faster than the cylinder it will advance farther and farther from element *h*, as shown in the diagram for each 45°. When the magnet has reached the last position shown D, it will have rotated through the angle *f*F, while the element *h*, has rotated the lesser angle *a*A, the difference indicated by ϕ being the amount by which the armature has *slipped*. *By definition* then, *slip is the difference between the speed of the rotating magnetic field and the speed of the armature;* it is measured in per cent of the synchronous speed or speed of the rotating magnetic field.

Ans. If the armature had no weight and there was no friction offered by the bearings and air, it would revolve in synchronism with the rotating magnetic field, that is, the slip would be zero; but since weight and friction are always present and constitute a small load, its speed of rotation will be a little less than that of the rotating magnetic field, so that induction will take place, in amount sufficient to produce a torque that will balance the load.



FIGS 2,632.—Allis Chalmers squirrel cage armature for polyphase induction motor. ***In construction,*** the armature core is built up of steel laminations mounted on a cast iron spider, the arms of which are shaped as fan blades to force air through the motor. The armature winding consists of rectangular copper bars, one in each slot, held in place by the tips of the overhanging teeth. The bars are fastened by copper rivets at each end to the end rings which are also of rectangular section. These rivets are expanded to completely fill the holes in the bars and end rings and are riveted under heavy pressure. In addition to the riveting, the joints are also brazed with silver solder thus forming joints that will not deteriorate either mechanically or electrically.

Ques. How is slip expressed?

Ans. In terms of synchronism, that is, as a percentage of the speed of the rotating magnetic field.

The slip is obtained from the following formula:

$$\text{Slip (rev. per sec.)} = S_f - S_a$$

or, expressed as a percentage of synchronism, that is, of the synchronous speed,

$$\text{Slip (\%)} = \frac{(S_f - S_a \times 100}{S_f}$$

where

S_f = synchronous speed, or *r.p.m.* of the rotating magnetic field;

S_a = speed of the armature.

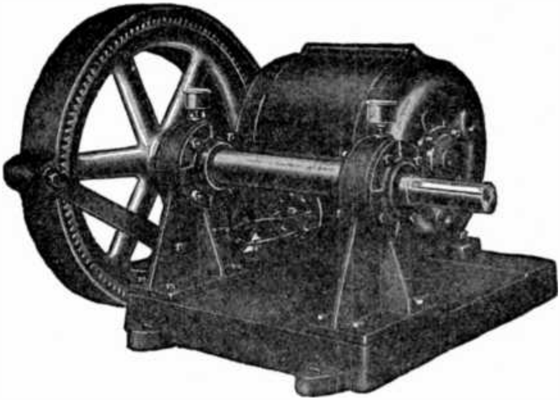


FIG. 2,633.—Triumph back geared polyphase induction motor. A great many applications, especially for direct attachment, require the use of either a very slow or special speed motor. As these are quite costly, the preferable arrangement, and one equally as satisfactory, is the use of a standard speed motor combined with a back geared attachment. Rawhide pinions are furnished whenever possible, insuring smooth running with a minimum of noise.

The synchronous speed is determined the same as for synchronous motor by use of the following formula:

$$S_f = \frac{2_f}{P} \times 60$$

where

S_f = synchronous speed or *r.p.m.* of the rotating magnetic field;

P = Number of poles;

f = frequency.

The following table gives the synchronous speed for various frequencies and different numbers of poles:

Table of Synchronous Speeds

Frequency	R.P.M. of the rotating magnetic field, when number of poles is					
	2	6	10	16	20	24
25	1,500	500	300	188	150	125
60	3,600	1,200	720	450	360	300
80	4,800	1,600	960	600	480	400
100	6,000	2,000	1,200	750	600	500
120	7,200	2,400	1,440	900	720	600
125	7,500	2,500	1,500	938	750	625

Ques. How does the slip vary?

Ans. Ordinarily it varies from about 1 per cent. to 4 per cent.

In badly designed, or special motors, and overloaded motors the slip is greater.

Ques. Why is the slip ordinarily so small?

Ans. Because of the very low resistance of the armature, very little pressure is required to produce currents therein, of sufficient strength to give the required torque.

Hence, the necessary rate of cutting the magnetic lines to induce this pressure in the armature is reached with very little difference between the field speed and armature speed, that is, with very little slip.

Ques. How does the slip vary with the load?

Ans. The greater the load, the greater the slip.

In other words, if the load increase, the motor will run slower, and the slip will increase. With the increased slip, the induced currents and the driving force will further increase. If the motor be well designed so that the field strength is constant and the lag of the armature currents is small, the driving force developed, or *torque*, will be proportional to the slip, that is the slip will increase automatically as the load is increased, so that the *torque* will be proportional to the load.

Example.—A 60 cycle, sixteen pole, three phase motor has a slip at full load of 6 per cent; at what speed does the armature turn at full load?

$$\text{Synchronous speed} = 450\ r.p.m.$$

$$\text{Slip} = 450 \times 6 \text{ per cent} = 27\ r.p.m.$$

$$\text{Armature speed} = 450 - 27 = 423\ r.p.m.$$

Check

$$\text{Slip } (=\%) = \frac{\text{synchronous speed} - \text{armature speed}}{\text{synchronous speed}} \times 100$$

$$= \frac{450-423}{450} \times 100 = \frac{27}{450} \times 100 = 6 \text{ per cent}$$

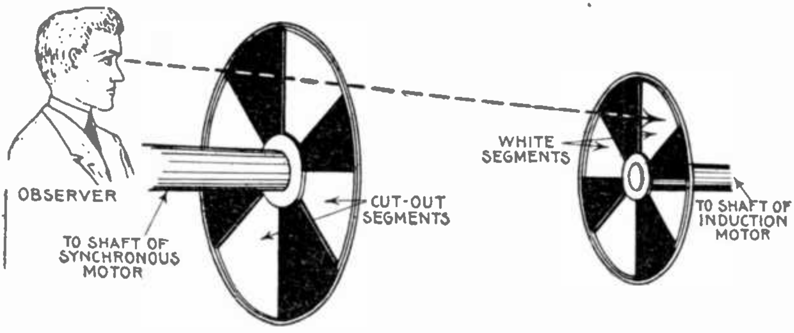
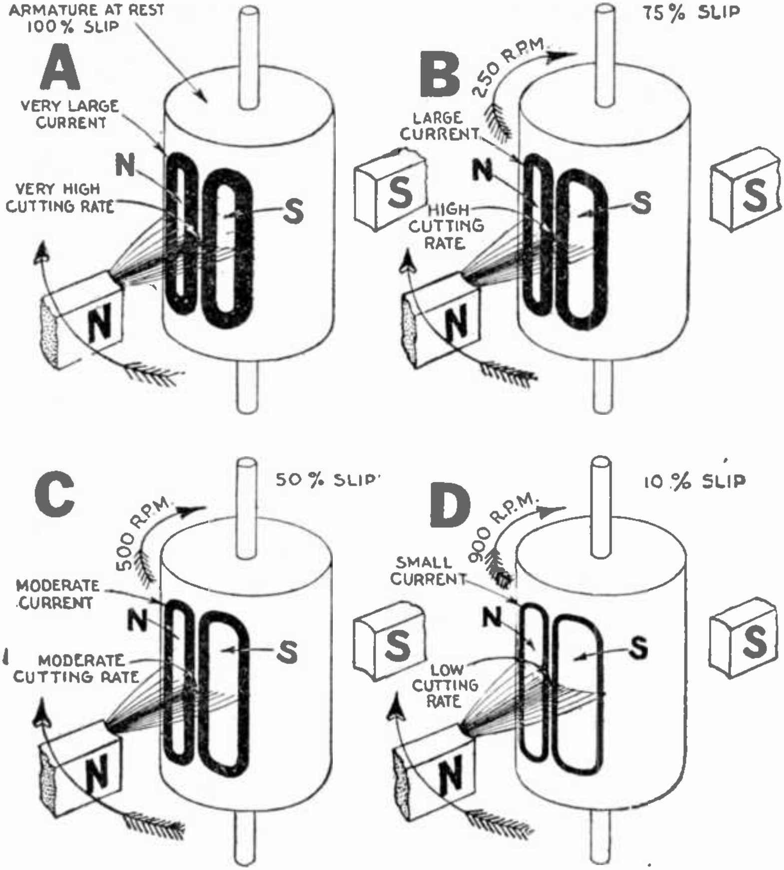


FIG. 2,634.—Sector method of measuring the slip of induction motors. A black disc having a number of white sectors (generally the same as the number of poles of the induction motor) is fastened with wax to shaft of the induction motor, and is observed through another disc having an equal number of sector shaped slits (that is a similar disc with the white sectors cut out) and attached to the shaft of a small self-starting synchronous motor, which is fitted with a revolution counter that can be thrown in or out of gear at will; then the slip (in terms of N_r) $= N \div (N_s \div N_r)$, in which: N = number of passages of the sectors; N_s = number of sectors; N_r = number of revolutions recorded by the counter during the period of observation. For large values of slip, the observations may be simplified by using only one sector ($N_s = 1$), then N will equal the slip in revolutions.

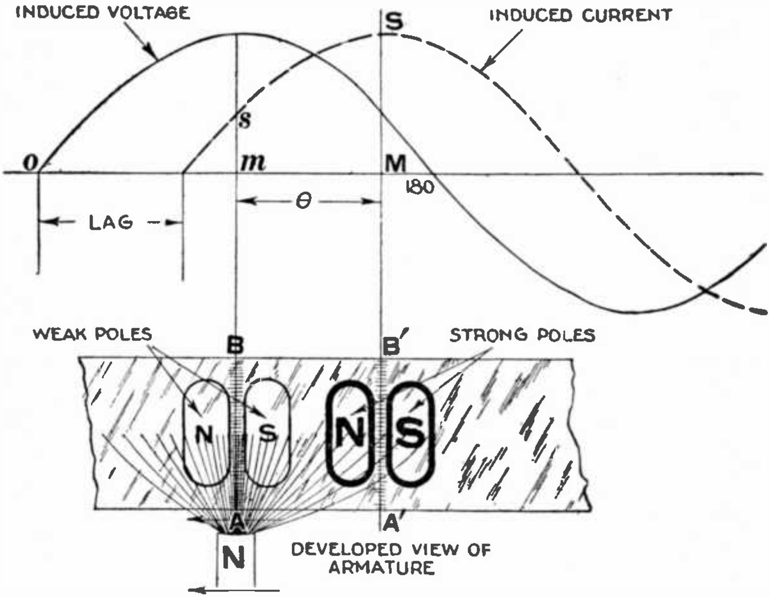


FIGS. 2,635 to 2,638.—Induction effect in starting of elementary cylinder type induction motor. The copper cylinder armature and rotating magnetic field of fig. 2,626 is here used to illustrate the starting action. Fig. A shows armature at rest with field revolving 1,000 *r.p.m.* The rate of "cutting" magnetic lines is very high which induces very large current eddies in the copper cylinder as indicated. The torque produced gradually increases the speed of the armature which causes decreasing frequency in the cutting of magnetic lines as indicated in figs. B, C, and D. The very large starting current in fig. A is permissible for small motors as they come up to speed quickly, but means must be provided to reduce the starting current in larger sizes. The effect of lag is not here considered.

Ques. Describe one way of measuring the slip.

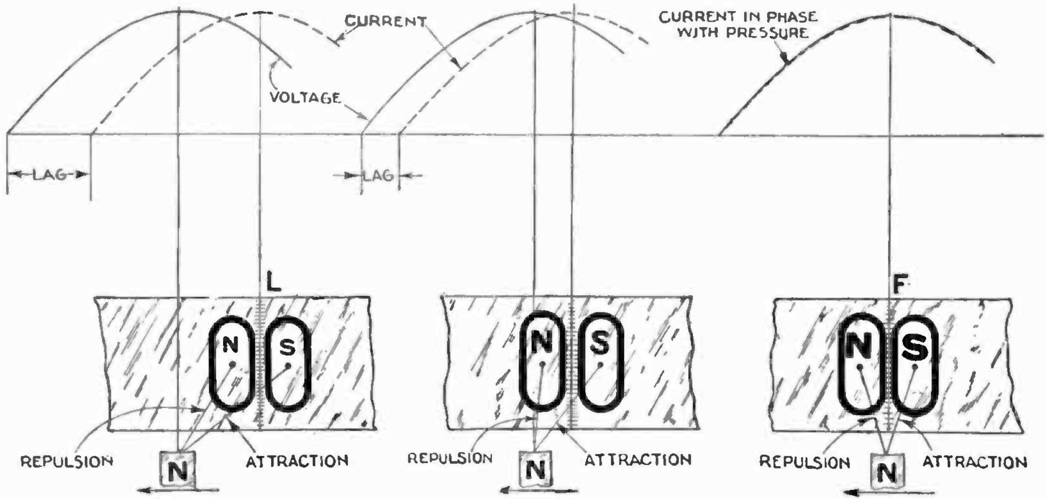
Ans. A simple though rough way is to observe simultaneously the speed of the armature and the frequency, calculating the slip from the data thus obtained, as on page 1,818.

This method is not accurate, as, even with the most careful readings, large errors cannot be avoided. A better way is shown in fig. 2,634.



Figs. 2,639 and 2,640.—Pressure and current sine curves and developed view of copper cylinder armature illustrating the effect of lag on the torque in starting a squirrel cage motor.

Starting Conditions of a Copper Cylinder Motor.—The total opposition of the copper cylinder or its *impedance* is made up of the actual or *ohmic* resistance of an element and its apparent or *spurious* resistance due to self-induction. In the ordinary squirrel cage bar the ohmic resistance is very low and the



FIGS. 2,641 to 2,643.—Diagram illustrating effect of decreasing lag on torque as a squirrel cage motor comes up to speed.

spurious resistance or *reactance* varies with the frequency referred to the armature. This frequency which produces the voltage in the armature bars or elements of the copper cylinder depends on the difference between the speed of the rotating magnetic field and the speed of the armature or copper cylinder.

Now in starting, the instant the motor is connected to the line, this difference is greatest which gives the maximum reactance which gradually decreases as the motor speeds up. The effect of this being to cause the current to lag behind the pressure in the element in question, especially at the beginning of the starting period. The sine curves of fig. 2,639 show the condition at this instant.

Now in fig. 2,639 the resultant rotation of the armature is to the right (assuming the field magnet stationary). As the armature begins to rotate, any bar as AB, at the center of the field will, because of lag, have only a small current induced in it as indicated by *ms*, fig. 2,639. This current will not reach a maximum MS, until the bar AB has receded from the magnet to the position A'B'. The induced poles at A'B', due to their remoteness from the magnet, are not effective in producing torque to turn the armature. At this instant the torque produced is due to the induced poles at AB. Here the attraction of unlike poles and repulsion of like poles both tend to cause the armature to rotate. These induced poles, however, have little strength because, as explained, only a small current is flowing in bar AB, hence only a small initial torque is produced.

The conditions during the starting period, that is, while the motor is coming up to speed, are progressively shown in figs. 2,641 to 2,643. Here it will be seen that as the reactance decreases due to the decrease of frequency which produces voltage in the armature bars, the lag also decreases. The effect of this is to bring the induced poles from a remote position L, to a position F, central with the magnets where they produce maximum torque. These diagrams (figs. 2,641 to 2,643) are given to explain the operation of the copper cylinder (shown in fig. 2,626) under conditions of variable frequency referred to the armature, such as occurs in starting.

It should be noted that in the cylinder arrangement *no definite paths are provided for the eddies and obviously a better result is obtained if the downward returning current of the eddies be led into some path where they will return across a field of* **opposite polarity** *from across that which they ascended*, as in such case the turning effect will be considerably increased."

In fig. 2,626, it is seen that the eddies comprising currents running in different directions are actually induced in a field of the same polarity and it is only due to ***the difference in intensity of two pressures acting in the same direction that causes the eddies***, as explained in fig. 2,628.

The principles just given for the elementary copper cylinder armature, as applied to the modern squirrel cage armature where definite paths are provided for the eddies, are given on pages 1,828 to 1,838.

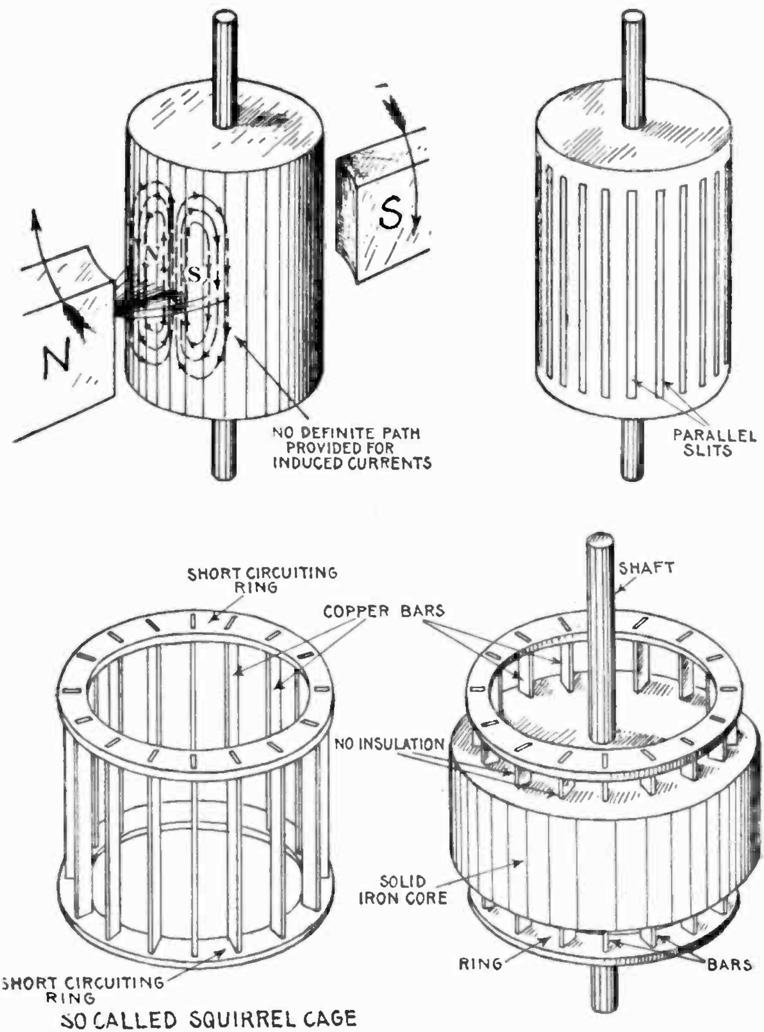
Before applying the principles just given for the copper cylinder to the squirrel cage, its evolution and construction should be considered as presented in the next section and accompanying illustrations.

Evolution of the Squirrel Cage Armature.—In the early experiments with rotating magnetic fields, copper discs were used: in fact, it was then discovered that *a mass of copper or any conducting metal, if placed in a rotating magnetic field, will be urged in the direction of rotation of the field.*

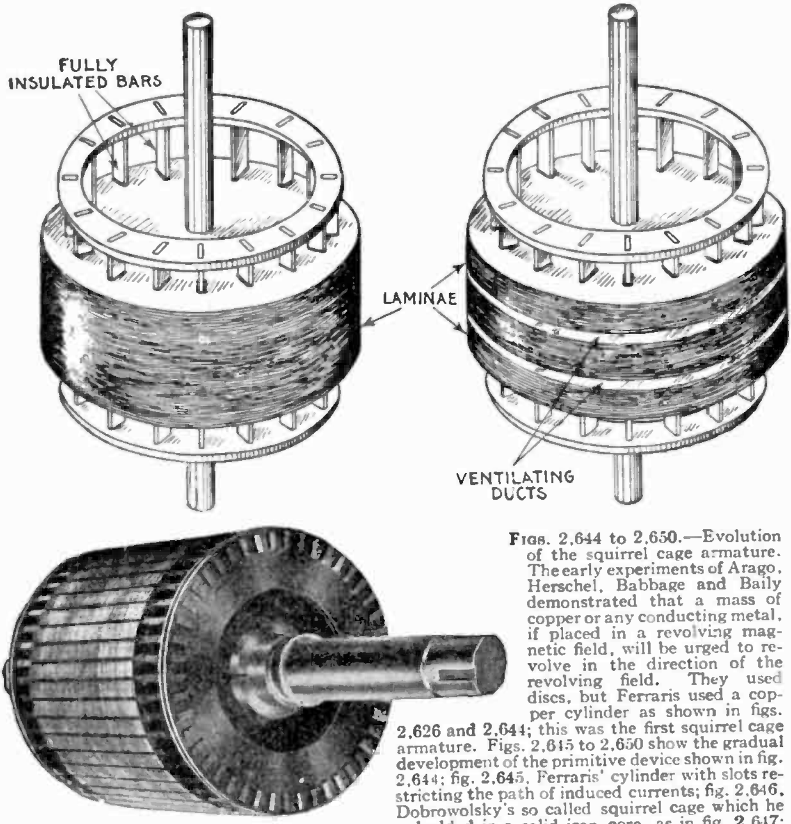
Ferraris used a copper cylinder as in figs. 2,626 and 2,644, which was the first step in the evolution of the squirrel cage armature. The trouble with an armature of this kind is that there are no definite paths provided for the induced currents.

Obviously, a better result is obtained if, in fig. 2,644, the downward returning currents of the eddies are led into some path where they will return across a field of opposite polarity from that across which they ascended, as in such case, the turning effect will be increased. Accordingly the design of fig. 2,644 was modified by cutting a number of parallel slits which extended nearly to the ends, leaving at each end an uninterrupted "ring" of metal. This may be called the first squirrel cage armature, and in the later development Dobrowolsky was the first to employ a built-up construction, using a number of bars joined together by a ring at each end, as in fig. 2,646, and embedded in a solid mass of iron, as in fig. 2,647; he regarding the bars merely as veins of copper lying buried in the iron.

A solid cylinder of iron will of course serve as an armature, as it is magnetically excellent; but the high specific resistance of iron prevents the flow of induced currents taking place sufficiently copiously; hence a solid cylinder of iron is improved by surrounding it with a mantle of copper, or by a squirrel cage of copper bars (like fig. 2,646), or by embedding rods of copper (short circuited together at their ends with rings) in holes just beneath its surface. However, since all eddy currents that circle round, as those sketched in fig. 2,644, are not so efficient in their mechanical effect as currents confined to proper paths, and as they consume power and spend it in heating effects, the core was constructed with laminations lightly insulated from each other, and further the squirrel cage copper bar inductors were fully insulated from contact with the core. Tunnel slots were later replaced by designs with open tops.



Figs. 2,644 to 2,650,—*Text on next page.*



FIGS. 2,644 to 2,650.—Evolution of the squirrel cage armature. The early experiments of Arago, Herschel, Babbage and Baily demonstrated that a mass of copper or any conducting metal, if placed in a revolving magnetic field, will be urged to revolve in the direction of the revolving field. They used discs, but Ferraris used a copper cylinder as shown in figs. 2,626 and 2,644; this was the first squirrel cage armature. Figs. 2,645 to 2,650 show the gradual development of the primitive device shown in fig. 2,644; fig. 2,645, Ferraris' cylinder with slots restricting the path of induced currents; fig. 2,646, Dobrowolsky's so called squirrel cage which he embedded in a solid iron core, as in fig. 2,647; fig. 2,648, design with insulated bars and laminated core to prevent eddy currents in the core; fig. 2,649, laminated core with ventilating ducts; fig. 2,650, modern squirrel cage armature representing the latest practice as built by Mechanical Appliance Co. The core is built up of discs punched from No. 29 gauge electrical sheet, insulated from each other and firmly clamped between end plates locked on the shaft. The slots in the discs are of the same general form as those in the core. Heavy fibre end pieces, punched to match the discs are placed at each end of the core, to prevent the bars coming in contact with the sharp edges of the teeth. The winding is made up of rectangular copper bars, passing through slots in the core, and short circuited on each other by means of copper end rings of special design. The bars are pressed into holes punched in the end rings, and the contact is then protected from corrosion by being dipped in a solder bath. The bars are insulated from the iron of the core by fibre cells projecting beyond the end of the slot. To secure ventilation the short circuiting rings are set some distance from the end of the core. In this way the bars between the core and the ring act as the vanes of a pressure blower, forcing a large volume of air through the field coils and ventilating openings.

Fig. 2,650 shows a modern squirrel cage armature conforming to the latest practice, other designs being illustrated in the numerous accompanying cuts.

In the smaller sizes, the core laminæ may be the solid type, but for the larger motors the core consists of a spider and segmental discs.

Operation of the Squirrel Cage.—The copper cylinder form of armature was found very inefficient because as stated *no definite paths were provided for the eddies;* moreover, these eddies,

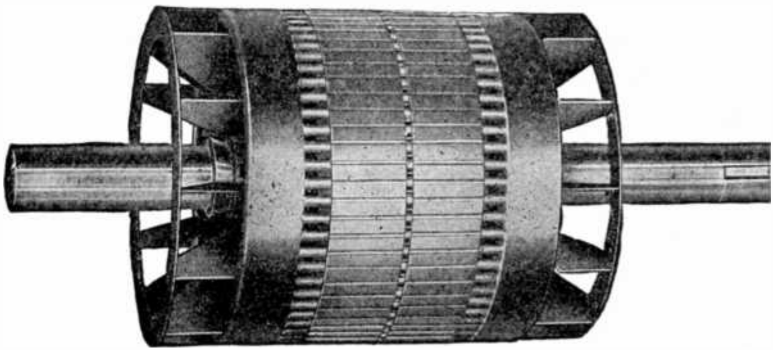


Fig. 2,651.—Century squirrel cage armature. *It consists of* 1, shaft; 2, armature laminations; 3, inductor bars; 4, end rings; 5, end flanges; 6, ventilating fans.

formed in a field of the same polarity by the very small difference in pressure of two unequal pressures acting in the same direction induced very weak poles in the armature resulting in very little torque.

Obviously, as stated, a better result is obtained if *the downward returning currents of the eddies be led into some path where* *they* will return across a field of **opposite polarity** *from across that which they ascended.*

In other words, to obtain the best turning effect, *the downward returning currents should be led across a strong field of reverse polarity.* Under the latter condition the eddies will be much stronger and the induced poles likewise.

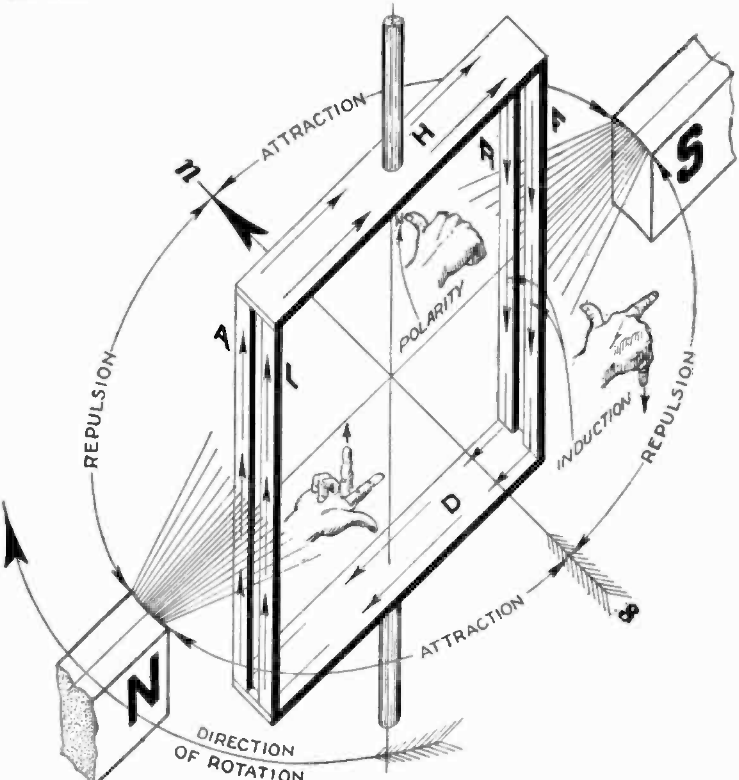


FIG. 2,652.—***Squirrel cage principles. 1.*** Elementary four bar squirrel cage and rotating field with application of *right hand rule* for direction of induced polarity, and *Fleming's rule* for direction of induced current *showing the polarization of the cage upon which the torque depends.* The plates H and D, form connecting links for the bars L, A, and R, F, thus completing the circuits for the induced current.

First consider a very elementary form of squirrel cage as shown in fig. 2,652, consisting of two pairs of copper bars L,A,R,F, connected by two copper plates H and D, at top and bottom respectively.

Now at the instant depicted, strong currents would be induced upward in bars A and L, which would pass across the top through plate H, and be urged downward through bars R and F, by the induction in the *field of* ***opposite polarity*** on that side. Thus the *strong* inductive effect in R

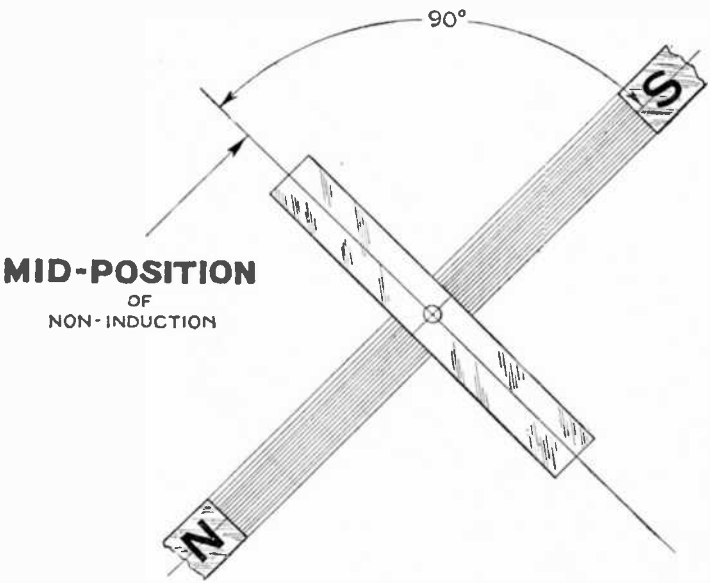


FIG. 2,653.—***Squirrel cage principles. 2.*** Top view of elementary four bar squirrel cage and rotating field (straight line of force) showing *mid-position of non-induction.*

and F, is added to the *strong* inductive effect in A and L. Here, it should be noted that the full pressure due to induction is available instead of just a small difference of two very nearly equal pressures as in fig. 2,628.

The strong currents flowing around the cage as indicated by the arrows will polarize the cage in the direction of the large arrow *ns*, and at the instant shown the cage would be urged to turn in a clockwise direction (looking down from the top) by *two pairs of forces of **attraction** and **repulsion*** as indicated in (fig. 2,652).

With this arrangement this urge or torque will last only momentarily because since there must be slip in order that the bars L,A,R,F, will cut the magnetic lines and cause induction of the eddies, the bars, which are rotating in the same direction as the field, *but slower*, will soon pass out of the field with result that the induction (and likewise eddies) will stop.

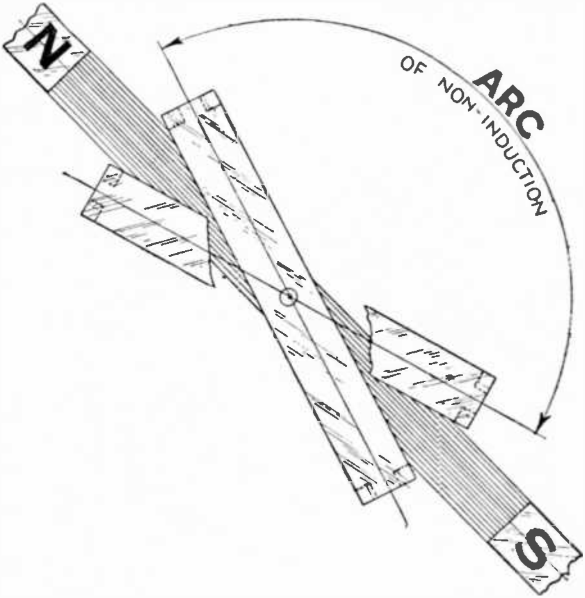


FIG. 2,654.—***Squirrel cage principles 3.*** Top view of elementary four bar squirrel cage and rotating field showing *extensive zones or periods in which there is no induction and consequently no torque produced.*

Fig. 2,653 shows the mid-position of non-induction and fig. 2,654, the angle through which the bars turn, during which there is no inductive effect.

Clearly, the four bar squirrel cage is very inefficient as induction takes place intermittently.

In fact the greater part of the revolution of the field (relative to the squirrel cage) there is no induction, because the number of lines of force threading through the cage is neither increased nor diminished.

The conditions are actually not quite as bad as here depicted because the lines of force are assumed to be straight (to emphasize the intermittent action) whereas the field is extended laterally, the lines being circular as indicated by the familiar experiment with magnet (cardboard and filings, see page 169, vol. 1). However, the strong region of the field lies directly between the poles, so that, the weaker field at the sides may be disregarded.

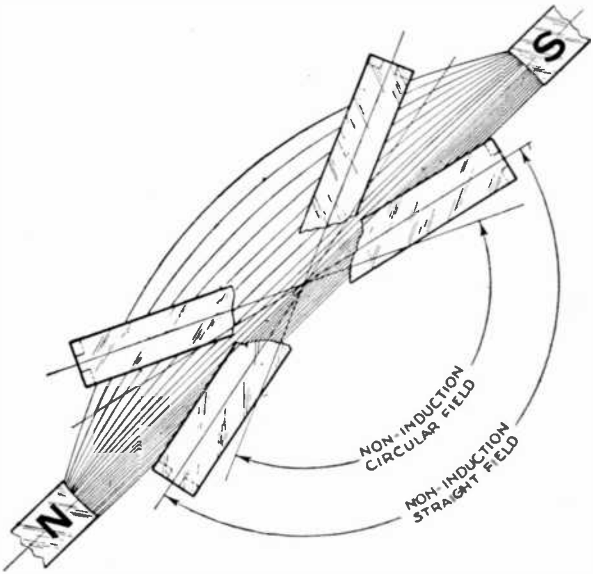


FIG. 2,655.—*Squirrel cage principles 4.* Top view of elementary four bar squirrel cage and rotating field (curved lines of force) showing zones of non-induction, weak and strong induction.

The intermittent action of the four bar squirrel cage may be overcome by increasing the number of bars.

In the modern squirrel cage there is a multiplicity of bars arranged concentrically around a shaft, being connected at top and bottom by short circuiting rings for instance as shown in figs. 2,632 and 2,691.

Fig. 2,656 shows a cage having a few more bars than the four bar cage and will serve to illustrate the non-intermittent action due to an increase in the number of bars.

Here bars L and F, are shown passing through the dense region of the field, bars H and *d*, entering the outer limits and bars D and *h*, passing out of the field. Accordingly, induction will be strong in bars L and F,

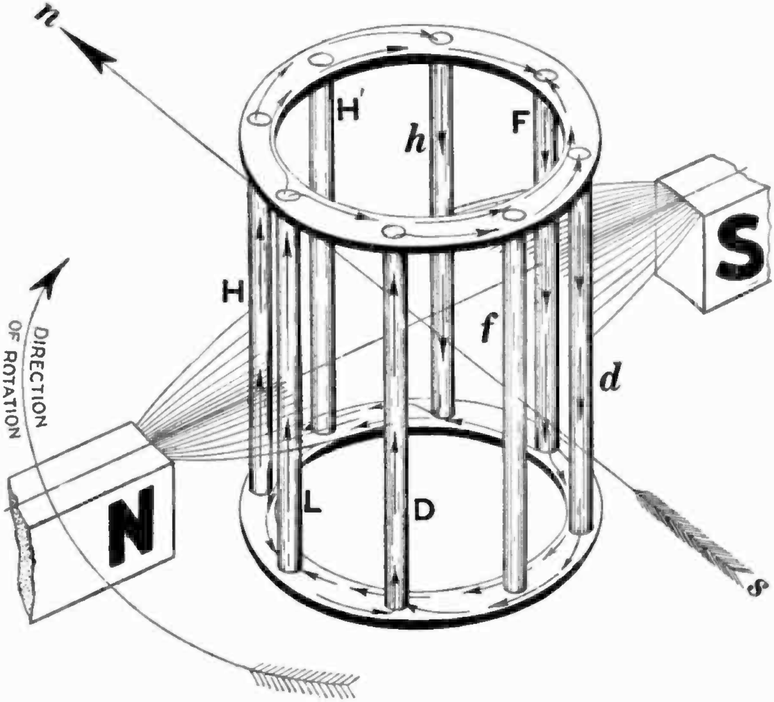
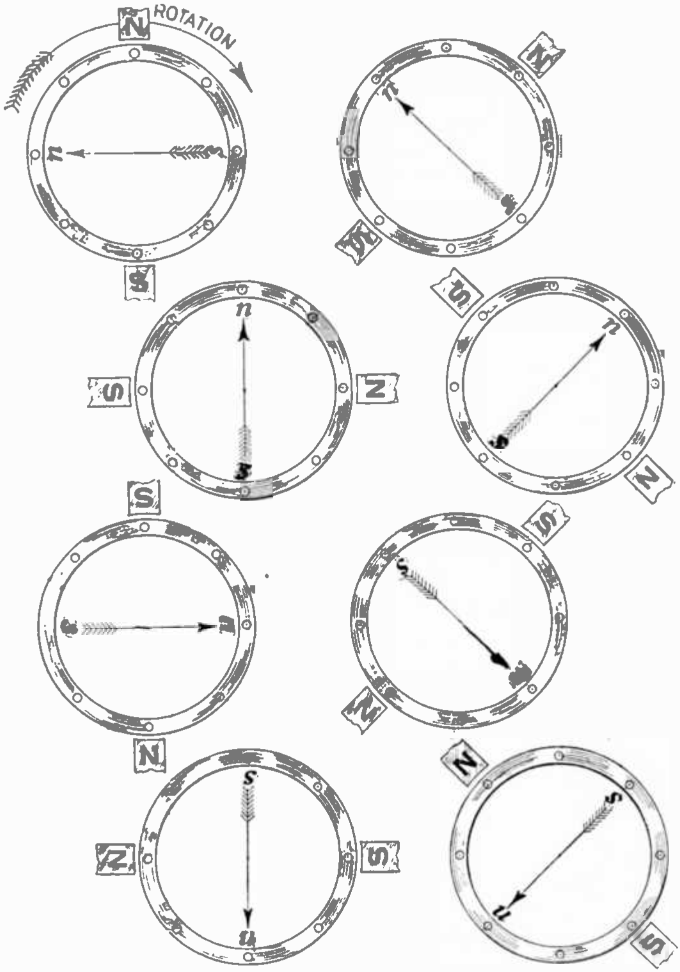


FIG. 2,656.—***Squirrel cage principles.*** *3.* Elementary eight bar squirrel cage and rotating field showing that *an increase in the number of bars will cause the torque to become nearer constant and stronger.*



FIGS. 2,657 to 2,664.—*Squirrel cage principles. 4.* Elementary eignt bar squirrel cage and rotating field for each 45° advance of the field around the squirrel cage showing *cycle of polarization.*

and weak in the two pairs of bars H,*h*, and D,*d*, with result that the armature will be strongly polarized in the direction *ns*, by bars L, F, to which will be added the relatively weak polarization due to the two pairs of bars H,*h*, and D,*d*. Now, evidently this condition for the bars mentioned will last only momentarily and as the rotation of the cage *falls behind* that of the field due to *slip*, the condition just described will be

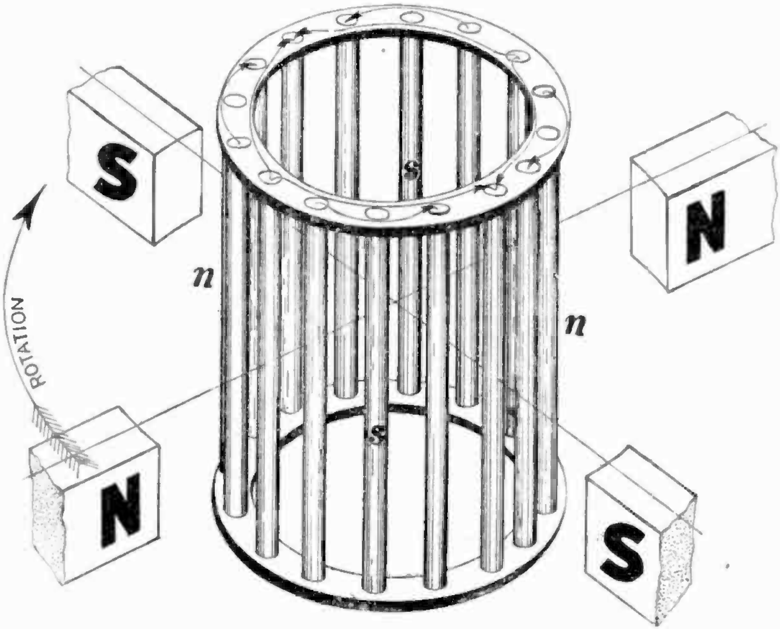


FIG. 2,665.—***Squirrel cage principles 7.*** Elementary sixteen bar squirrel cage and four pole rotating field showing *distribution of the induced currents in the armature with resulting approach to continuous and constant torque due to increase of bars and poles.*

advanced to the next set of bars; that is, induction will be strong in bars H and *d*, and weak in the two pairs of bars H′,F, and L, *f*.—and similarly all around the cage as the rotation of the field advances on that of the cage.

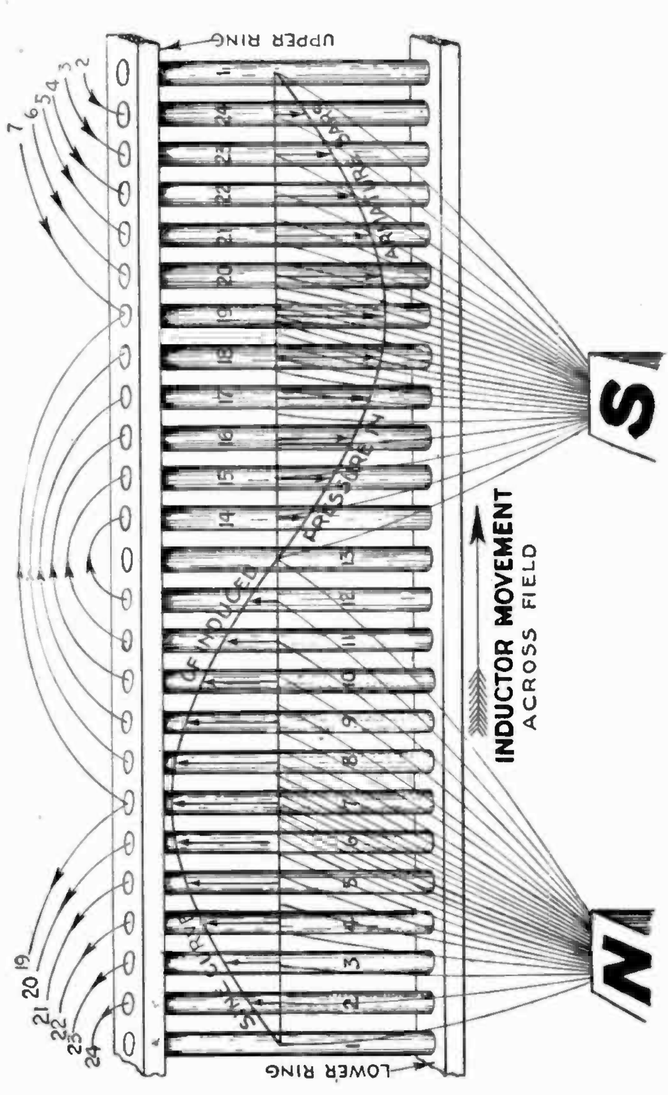


FIG. 2,666.—*Squirrel cage principles 8.* Developed view of 24 bar squirrel cage in bipolar field showing distribution of the field and induced voltages in the bars. The relative lengths of the arrows terminating at the sine curve gives the relative magnitudes of the voltages in their respective inductors, and the arrow heads, the directions of the resulting currents. The paths of the currents for the upper ring are as indicated. Similar paths are taken in the lower ring but in reverse direction.

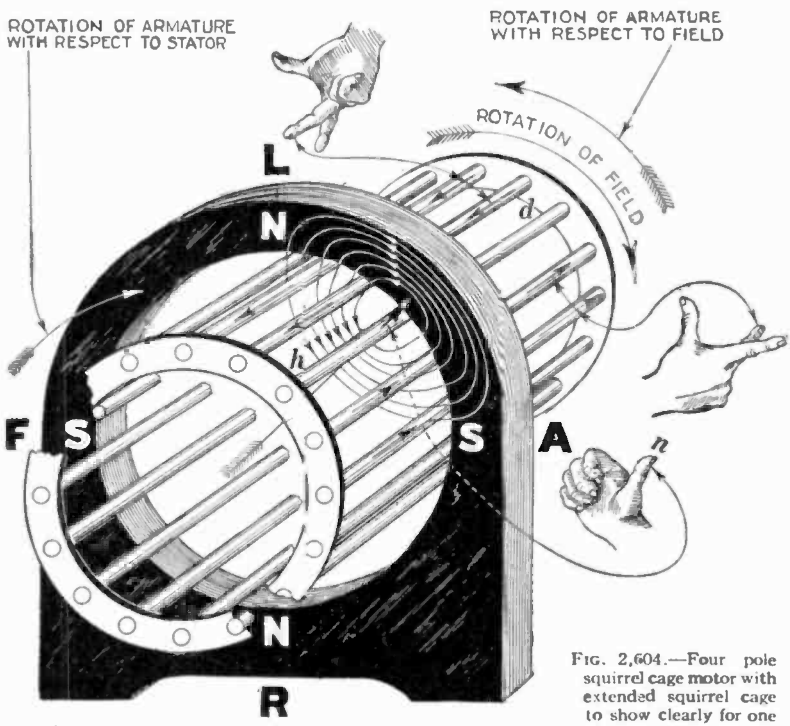


FIG. 2,604.—Four pole squirrel cage motor with extended squirrel cage to show clearly for one quadrant magnetic field distribution and induced polarization of the squirrel cage. *At any instant* there is a maximum field density at four points in the stator, as at L, A, R, F, for the instant here shown, there being north poles at L, and R, and south poles at A, and F. With clockwise field rotation, currents will be induced in the squirrel cage as shown, resulting in a north pole through bar *hd*. This produces the torque both by repulsion and attraction, tending to rotate the squirrel cage clockwise.

NOTE.—***Speed and torque relation.*** When an induction motor is running at zero load, but little torque is required to drive it, and the armature revolves at a speed but very little less than the speed of the rotating magnetic field (the speed of the rotating magnetic field is called the synchronous speed). The armature cannot, however, reach full synchronous speed because at synchronous speed the armature inductors would move along with the rotating magnetic field; there would be no voltage and therefore no current induced in the armature inductors; and consequently the field magnetism could exert no driving force on the armature inductors. When an induction motor is running with a load, the driving torque must be large, and therefore the current in the armature inductors must be large in order that the armature magnetism may exert the necessary driving force upon the armature inductors; furthermore the induced voltage in the armature inductors must be sufficient to produce the necessary armature currents, and to do this the armature must run appreciably below synchronism

Evidently, as the number of bars is increased, the torque becomes nearer constant even with the elementary field shown in the diagram and with a modern squirrel cage having a multiplicity of bars such as shown in fig. 2,665, and a multi-pole field, the torque is practically constant and of considerable strength as compared with the elementary machines illustrated in the diagrams just given.

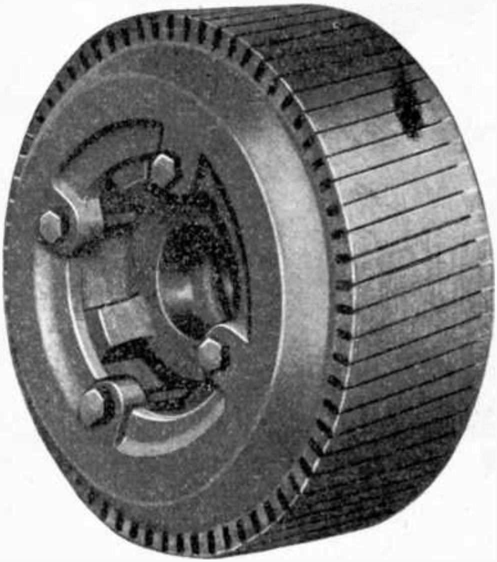


FIG. 2,671. — Fairbanks-Morse squirrel cage armature core construction. The cores are made up of laminations clamped between heads. In the larger sizes these cores are mounted on spiders giving ventilation through the core.

The Field Magnets.—The construction of the field magnets, which, when energized with alternating current produce the rotating magnetic field, is in many respects identical with the armature construction of revolving field alternators.

Broadly, the field magnets of induction motors consists of:

1. Yoke or frame;
2. Laminæ, or core stampings;
3. Winding.

Ques. What is the construction of the yoke and laminæ?

Ans. They are in every way similar to the armature frame and core construction of revolving field alternators.

Field Windings of Induction Motors.—The field windings of induction motors are almost always made to produce more than two poles in order that the speed may not be unreasonably high. This will be seen from the following:

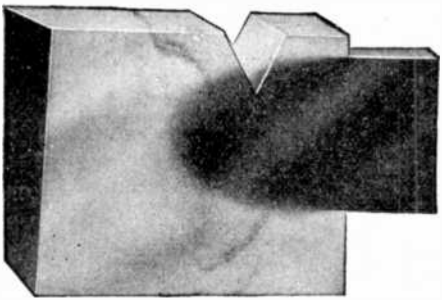


FIG. 2,672.—Section of Fairbanks-Morse "cast-on" joint showing union of end ring and inductor. The view shows the V-shape inspection groove as described in fig. 2,700.

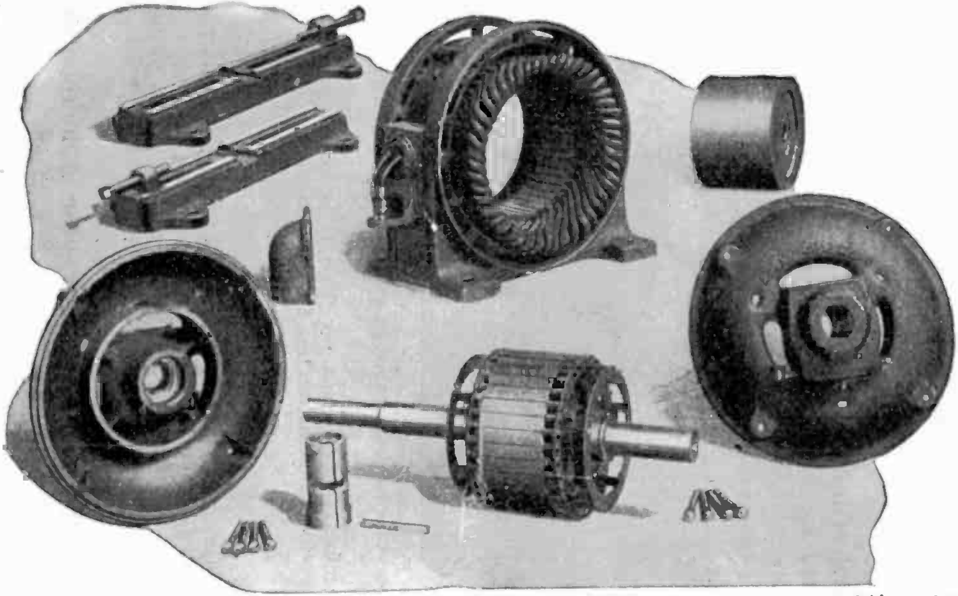
If P, be the number of *pairs* of poles per phase, *f*, the frequency, and N, the number of revolutions of the rotating field per minute, then

$$N = \frac{60 \times f}{P}$$

Thus for a frequency of 100 and one pair of poles, $N = 60 \times 100 \div 1 = 6{,}000$. By increasing the number of pairs of poles to 10, the frequency remaining the same, $N = 60 \times 100 \div 10 = 600$. Hence, in design, by increasing the number of pairs of poles the speed of the motor is reduced.

Ques. State an objection to very high speed of the rotating field.

Ans. The more rapid the rotation of the field, the greater is the starting difficulty.



Figs. 2,673 to 2,690.—Disassembly of Allis-Chalmers type AR belted squirrel cage induction motor showing field armature, etc.

Ques. Besides employing a multiplicity of poles, what other means is used to reduce the speed?

Ans. Reducing the frequency.

Ques. What difficulty is encountered with low frequency currents?

Ans. If the frequency be very low, the current would not be suitable for incandescent lamp lighting, because at low frequency the rise and fall of the current in the lamps is perceptible.

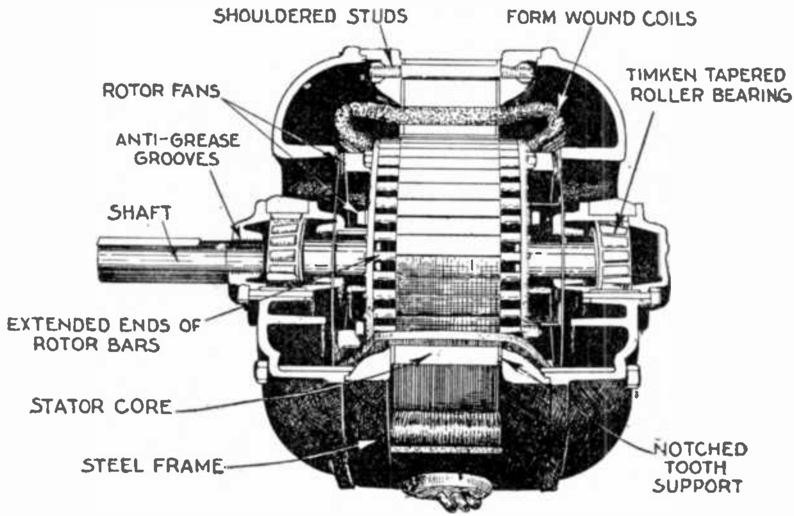


FIG. 2,691.—Sectional view of Allis-Chalmers polyphase squirrel cage induction motor.

Ques. What is the general character of the field winding?

Ans. The field core slots contain a distributed winding of substantially the same character as the armature winding of a revolving field polyphase alternator.

Ques. Are the poles formed in the usual way?

Ans. They are produced by properly connecting the groups of coils and not by windings concentrated at certain points on salient poles or separately projecting masses of iron, as in direct current machines.

Ques. How are the coils grouped?

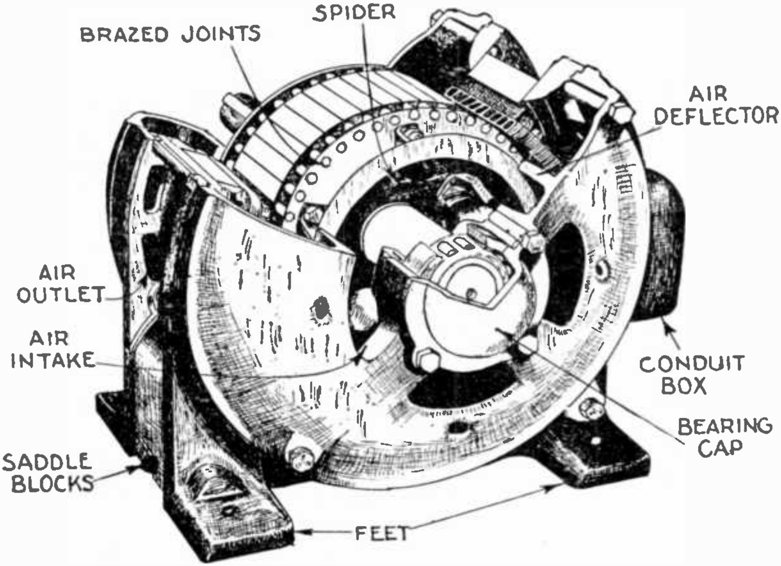


FIG. 2,692.—Sectional view of Allis-Chalmers polyphase squirrel cage induction motor.

Ans. Three phase windings are usually Y connected.

Ques. What other arrangement is sometimes used?

Ans. In some cases Y grouping is used for starting and Δ grouping for running.

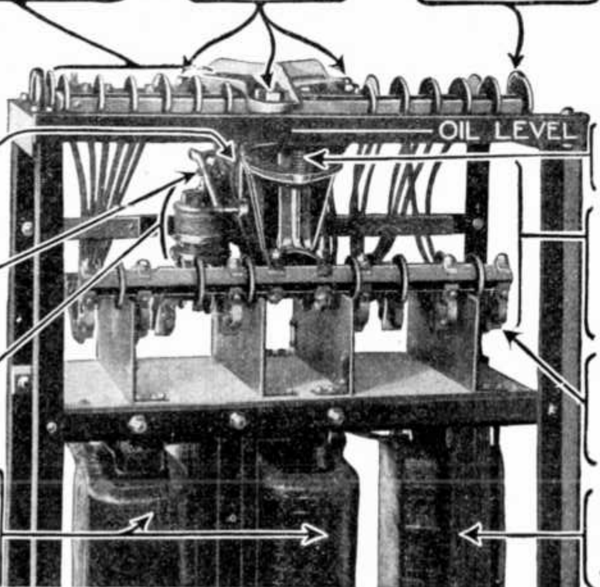


FIG. 2,693.—E. C. and M automatic high voltage compensator removed from the oil tank to show construction. *In operation*, the double throw action of the switching mechanism is obtained by a magnet which compresses a spring when the starting contacts are engaged, and a relay which trips a knee joint toggle when the motor is up to speed, causing the starting contacts to open and the running contacts to close.

Starting of Induction Motors.—It must be evident that if the field winding of an induction motor whose armature is at rest, be connected directly in the circuit without using any starting device, the machine is placed in the same condition as a transformer with the secondary short circuited and the primary connected to the supply circuit.

Owing to the very low resistance of the armature, the machine, unless

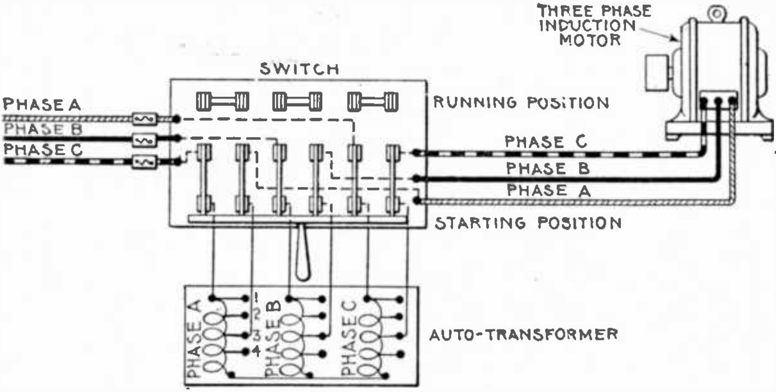


FIG. 2,694.—Auto-transformer or compensator connections for three phase induction motor. In operation when the double throw switch is thrown over to starting position, the current for each phase of the motor flows through an auto-transformer, which consists of a choking coil for each phase, arranged so that the current may be made to pass through any portion of it (as 1, 2, 3) to reduce the voltage to the proper amount for starting. After the motor has come up to speed on the reduced voltage, the switch is thrown over to running position, thus supplying the full line voltage to the motor. In actual construction fuses are usually connected, so that they will be in circuit in the running position, but not in the starting position, where they might be blown by the large starting current.

it be of very small size, would probably be destroyed by the heat generated before it could come up to speed. Accordingly some form of starting device is necessary.

There are several methods of starting, as with:

1. Resistances in the field;
2. Auto-transformer or compensator;
3. Resistance in armature.

Ques. Explain the method of inserting resistances in the field.

Ans. Variable resistances are inserted in the circuits leading to the field magnets and mechanically arranged so that the

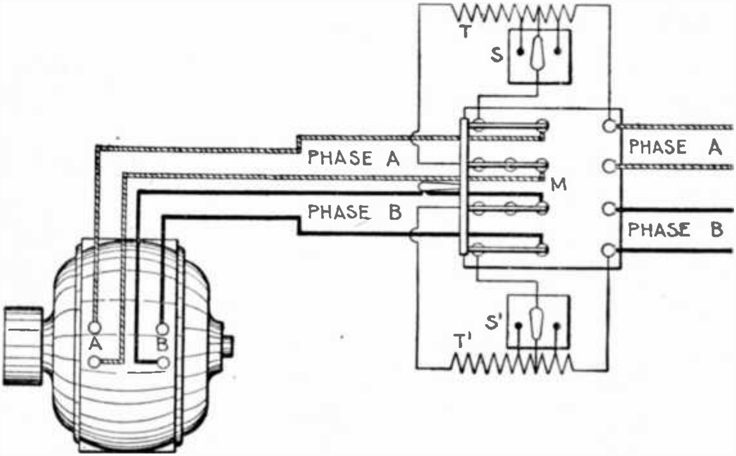


FIG. 2,695.—Westinghouse auto-starter. Polyphase induction motors may be started by connecting them directly to the circuit with an ordinary switch, and the smaller motors are started in this way in practice. In the larger motors, however, the starting torque at normal voltage is several times its full load torque; therefore, they are started on a reduced voltage, and the full pressure of the circuit is not applied until they have practically reached their operating speed. The figure shows connections with a two phase alternating current circuit. The auto-starter consists of two auto-transformers T and T′, each having only a single winding for both primary and secondary, which are tapped at certain points by switches, thus dividing the winding into a number of loops, so that one of several voltages may be applied for starting, and the starting torque thus adjusted to the work that has to be performed. At the highest points tapped by the switches S and S′, the full pressure, and at the lowest points, the lowest pressure, is applied to the motor by the operation of the main switch M. This switch has four blades and three positions. When thrown to the left as indicated, it connects the auto-transformers T and T′, across the circuits A and B, respectively, so that the pressure across the transformer coils, as determined by the position of the switches S and S′, is applied to the motor circuits A and B. The intermediate position of the switch M, interrupts both circuits. To start the motor, the switch M, is thrown to the left and a reduced pressure applied; after the motor has started and come up to speed the switch M, is thrown to the right, thus cutting out the transformer and connecting the motor directly to the circuit. The starting device can be located at a point remote from the motor, thus eliminating danger from fire due to possible sparks, in case where it is necessary to install the motors in grain elevators, woollen mills, or in any place exposed to inflammable gases, or floating particles of combustible matter. This feature is also valuable in cases where motors are suspended from the ceiling, or installed in places not easily accessible.

resistances are varied simultaneously for each phase in equal amounts. These starting resistances are enclosed in a box similar to a direct current motor rheostat.

Ques. Is this a good method?

Ans. It is more economical to insert a variable inductance in the circuit, by using an auto-transformer.

Ques. What is the auto-transformer or compensator method of starting?

Ans. It consists of reducing the pressure at the field terminals by interposing an impedance coil across the supply circuit and feeding the motor from variable points on its windings.

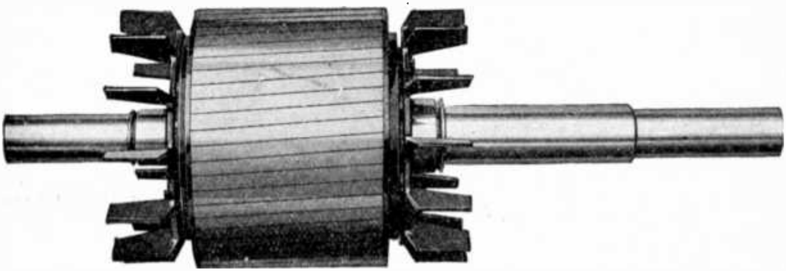


FIG. 2,696.—Louis Allis squirrel cage armature with skew slots and ventilation fans.

FIG. 2,697.—Robbins & Myers squirrel cage motor laminations. View shows both field and armature laminæ, also air gap.

Squirrel Cage Starting Current Torque.—Some variations may be expected in the relation of starting torque to current and in other characteristics between motors of a given horse power when wound for different frequencies or different speeds of a given frequency.

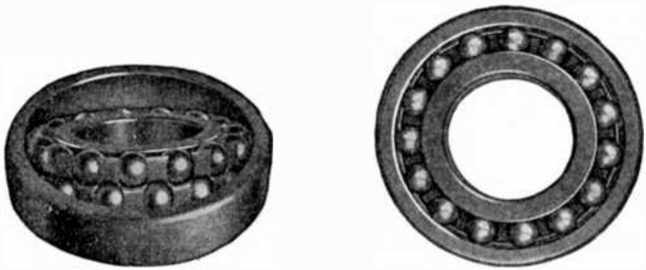
The following table prepared by Century Electric Co. gives maximum starting current and minimum static torque that may be expected with normal voltage maintained at the motor terminals.

Number of Poles	*Maximum Starting Current In Percentage of Full Load Current	Minimum Static Torque In Percentage of Full Load Torque
Fractional Horsepower 60 and 50 cycle		
4	450%	250%
6	415%	200%
Fractional Horsepower 25 cycle		
2	450%	250%
4	450%	200%
All other motor sizes not included above. 60, 50, 40 and 25 cycle		
2	450%	175%
4	450%	175%
6	415%	150%
8	415%	135%
10	375%	125%
12	375%	125%

**The starting current values, as given above, are 75% of the average static or locked rotor value without compensator or other current limiting device in the circuit.* (N. E. L. A. rule.)

The maximum or pull-out torque will in no case be found less than 200% of full load torque.

Power Factor of Induction Motors.—In the case of a direct current motor, the energy supplied is found by multiplying the current strength by the voltage, but in all induction motors the effect of self-induction causes the current to lag behind the pressure, thereby increasing the amount of current taken by the motor. Accordingly, as the increased current is not utilized by the motor in developing power, the value obtained by multiplying the current by the voltage represents an *apparent energy* which is greater than the real energy supplied to the motor.



FIGS. 2,698 and 2,699.—Double row, self aligning ball bearings that are used on Fairbanks-Morse horizontal shaft ball bearing motors.

It is evident, that if it were possible to eliminate the lag entirely, the real and apparent watts would be equal, and the power factor would be unity.

The importance of power factor and its effect upon both alternator capacity and voltage regulation is deserving of the most careful consideration with all electrical apparatus, in which an inherent phase difference exists between the pressure and the current, as for instance in static transformers and induction motors.

While the belief is current that any decrease in power factor from unity value does not demand any increase of mechanical output, this is not true, since all internal alternator and line losses manifest themselves as heat, the wasted energy to produce this heat being supplied by the prime mover.

Apart from the poor voltage regulation of alternators requiring abnormal field excitation to compensate for low power factor, some of the station's rated output is rendered unavailable and consequently produces no revenue. The poor steam economy of underloaded engines is also a serious source of fuel wastage.

Careful investigations have shown that the power factor of industrial plants using induction motor drive with units of various sizes will average

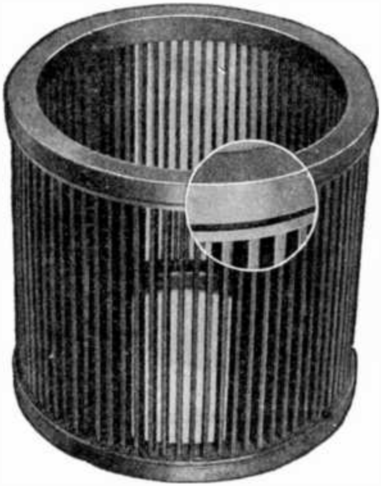


FIG. 2,700.—Appearance of Fairbanks-Morse squirrel cage if it could be removed from the core. The enlarged section shows the inspection groove cut in the end ring to prove the solidity of construction.

between 60 and 80 per cent. With plants supplying current to underloaded motors having inherently high lagging current values, a combined factor as low as 50 per cent. may be expected. Since standard alternators are seldom designed to carry their rated kilowatt load at less than 80 per cent power factor, the net available output is, therefore, considerably increased.

Speed and Torque of Motors.—The speed of an induction motor depends chiefly on the frequency of the circuit and runs within 5 per cent. of its rated speed; it will produce full torque if the line voltage do not vary more than 5 to 10 per cent.

At low voltage the speed will not be greatly reduced as in a direct current motor, but as the torque is low the motor is easily stopped when a load is thrown on.

The current taken by an induction motor from a constant pressure line varies with the speed as in a direct current motor. When a load is thrown on, the speed is reduced correspondingly and as the self-induction or reactance is diminished, more current circulates in the squirrel cage winding, which in turn reacts on the field coils in a similar manner and more current flows in them from the line. In this manner the motor automatically

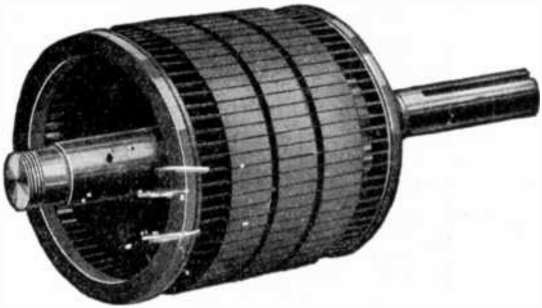


FIG. 2,701.—Fairbanks-Morse type H, squirrel cage armature mounted on shaft.

takes current from the line proportional to the load and maintains a nearly constant speed.

The so-called constant speed motors require slight variations in speed to automatically take current from the line when the load varies.

Induction motors vary in speed from 5 to 10 per cent., while synchronous motors vary but a fraction of one per cent.

Single phase motors to render efficient service must be able, where requisite, to develop sufficient turning moment or torque to accelerate, from standstill, loads possessing large inertia or excessive static friction; for example, meat choppers and grinders, sugar or laundry centrifugals; heavy punch presses; group driven machines running from countershafts with possible over taut belting, poor alignment, lubrication, etc.

Efficiency and Power Factor Curves.—From these curves it can readily be fixed in mind the relative efficiency and power factors for motors of different ratings and different speeds. These curves also bring out very well to just what degree a high rating at a high speed is superior to a low rating at a low speed.

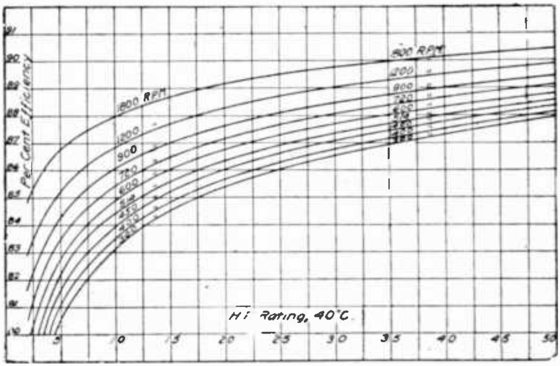


FIG. 2,702.—Efficiency of 60 cycle, squirrel cage induction motors at 100% load, 3 to 50 *h.p.*

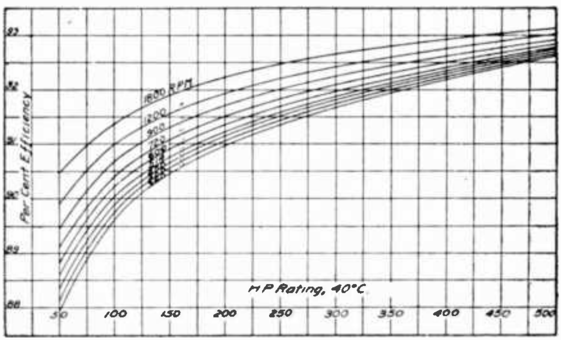


FIG. 2,703.—Efficiency of 60 cycle, squirrel cage induction motors at 100% load, 50 to 500 *h.p.*

It is true that these curves are for squirrel cage induction motors only, but may be used for slip ring wound armature induction motors by subtracting from .5 to 3.% depending on the size; that is, a slip ring motor has slightly lower efficiency and power factors than a squirrel cage motor.

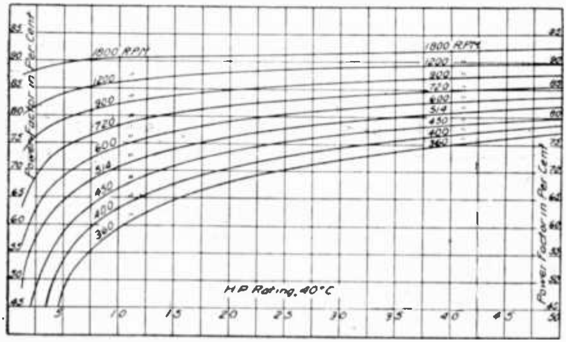


Fig. 2,701.—Efficiency of 60 cycle, squirrel cage induction motors at 100% load, 3 to 50 *h.p.*

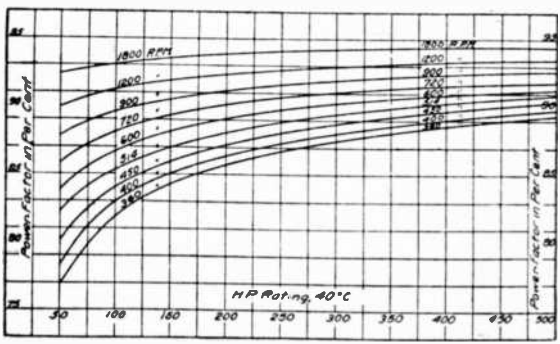


Fig. 2,705.—Power factor of 60 cycle, squirrel cage induction motors at 100% load, 50 to 500 *h.p.*

TEST QUESTIONS

1. *Define the term asynchronous.*
2. *Name two kinds of squirrel cage motors.*
3. *Describe briefly the operation of a single phase motor.*
4. *Why is a single phase induction motor not self-starting?*
5. *What provision is made for starting single phase induction motors?*
6. *Describe briefly the operation of a polyphase squirrel cage motor.*
7. *Why are induction motors called* asynchronous?
8. *How does the speed vary?*
9. *Define the term* slip.
10. *Why are induction motors sometimes called constant speed motors?*
11. *Why do some writers call the field magnets and armature the primary and secondary, respectively?*
12. *Why are polyphase induction motors usually presented in text books before single phase motors?*
13. *Describe the construction of a squirrel cage motor.*
14. *Upon what three conditions does the operation of a squirrel cage motor depend?*
15. *What is a rotating magnetic field and how is it produced?*
16. *Explain Arago's rotations.*
17. *What did Prof. Ferraris discover?*
18. *How is a rotating magnetic field produced by two phase current; how by three phase current?*
19. *What causes an induction motor to rotate?*

20. *When is the torque greatest?*
21. *Why is slip necessary in the operation of an induction motor?*
22. *How is slip expressed?*
23. *How does the slip vary?*
24. *Why is the slip ordinarily so small?*
25. *How does the slip vary with the load?*
26. *How is slip measured?*
27. *Describe the evolution of the squirrel cage armature.*
28. *How are field magnets constructed?*
29. *State an objection to very high speed of the rotating field.*
30. *Besides employing a multiplicity of poles what other means is used to reduce the speed?*
31. *What difficulty is encountered with low frequency currents?*
32. *What is the general character of the field winding?*
33. *Are the poles formed in the usual way?*
34. *How are the coils grouped?*
35. *Describe the methods of starting squirrel cage motors.*
36. *Which is the approved method of starting?*
37. *Describe an auto transformer or compensator.*