COYNE ELECTRICAL AND RADIO SCHOOL

REFERENCE ENCYCLOPEDIA

COYNE
Electrical School
CHICAGO ~~ ILLINOIS

ESTABLISHED 1899

DIRECT CURRENT POWER AND MACHINES

Section One

D. C. Generators
Construction and Operating Principles
Types of Generators and Their Applications
Operation and Care of Generators
Parallel Operation
Three Wire Generators and Balancers
Commutation and Interpoles
for Generators and Motors

D. C. GENERATORS

Direct current energy and machines are very extensively used for traction work and certain classes of industrial power drives.

The principal advantages of D. C. motors are their very excellent starting torque and wide range of speed control.

D. C. motors are excellent for operating certain classes of machines which are difficult to start under load, and must be driven at varying speeds, or perhaps reversed frequently. Their speed can be varied over a very wide range, both above and below normal speed.

Many thousands of factories and industrial plants use electric motors exclusively for driving their various machines, and in certain classes of this work D. C. motors are extensively used. They are made in sizes from 1/10 h. p. to several thousand horse power each, and are used both for group drive and individual drive of various machines.

Fig. 1 shows an installation of large D. C. motors in use in a steel mill. These motors are located in the power room as shown, and are connected to shafts extending through the wall at the right, to drive the great rolls which roll out the hot steel in the adjoining room.

Fig. 2 shows a smaller motor used for driving a metal working machine. Where a separate motor is used for each machine in this manner, it is classed as individual motor drive. Millions of electric motors are used in this manner in industrial plants.

For operation of street cars and elevated trains in cities, and electric railways across the country, series D. C. motors are extensively used, because their great starting torque enables them to easily start a loaded car or train from a standing position, and quickly bring it up to very high speeds.

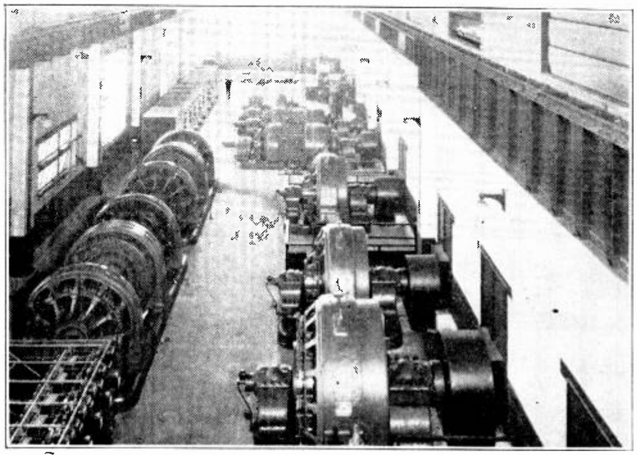


Fig. 1. This photo shows a group of large D. C. motors in use in a steel mill. Machines of this type, ranging from several hundred to several thousand horsepower each, are used in this work.

Fig. 3 shows a powerful electric locomotive which is driven by several electric motors of several hundred horse power each.

D. C. motors are commonly made to operate on voltages of 110, 220, and 440, for industrial service; and from 250 to 750 volts for railway service.

Elevators in large skyscraper office and store buildings also use thousands of powerful D. C. motors, to smoothly start the loaded cars and swiftly shoot them up or down, ten, forty, or 70 stories as desired.

Here again their good starting torque, smoothness of operation, and accurate control for stopping exactly at floor levels, make them very desirable.

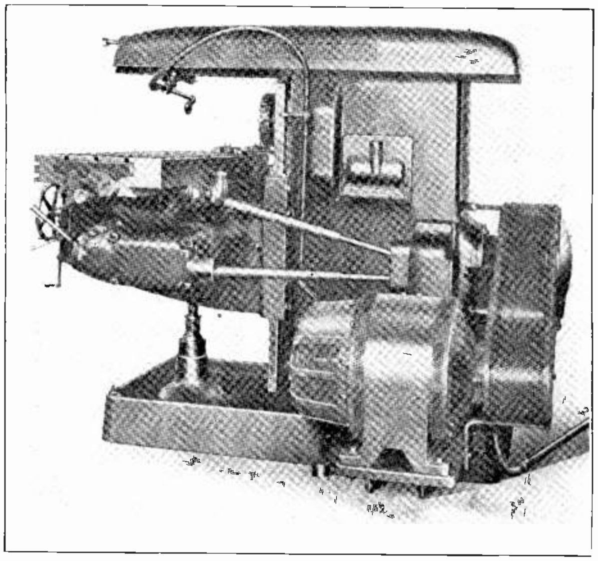


Fig. 2. Hundreds of thousands of small and medium sized motors are used to drive individual machines, as shown in this view.

One modern type of elevator equipment uses direct current motors and what is known as variable voltage control. The variable voltage for each elevator motor is supplied by a separate D. C. generator, which is designed to vary its voltage as the load on the car varies, thus providing even speed regulation and extremely smooth starting and stopping.

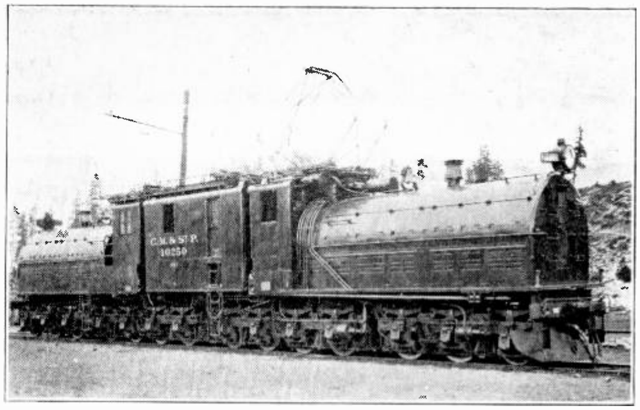


Fig. 3. Electrical locomotives of the above type often use six or eight powerful D. C. motors to turn their driving wheels.

Fig. 4 shows a large D. C. elevator motor with its cable drum and magnetic brake attached on the right hand side.

Because of the extensive use of direct current for elevators in large buildings, and for traction purposes, some large cities have their central business districts supplied with D. C., and the outlying districts where the power must be transmitted farther are supplied with A. C.

Direct current generators are used to supply the direct current wherever it is extensively used; and many privately owned power plants use D. C. generators because of the simplicity of their operation in parallel, where several are used.

In the operation of D. C. generators the speed at which they are driven is not as critical as it is with A. C. generators. Small D. C. generators can be belt driven; but this is not practical with A. C. generators, because a slight slip of the belt would cause their speed to vary, and make trouble in their parallel operation.

D. C. generators are made in sizes from 60 watts for automotive use, up to those of several thousand kilowatts for industrial and railway power plants. Their voltages range from 6 volts on automotive generators to 440 volts for industrial purposes; and on up to 600 and 750 volts for railway work.

The smaller sizes for belt drive operate at speeds from 300 to 1800 R. P. M., while the larger sizes which are direct connected to steam, oil, or gas engines, run at speeds from 60 to 250 R. P. M.

When these generators are driven by direct shaft connections to reciprocating steam engines, a large flywheel is usually provided on the same shaft to produce a more even speed. It will also deliver power to the generator during suddenly increased loads, until the engine governor can respond.

D. C. generators are not so well adapted for direct connection to steam turbines, because of the very high speeds of the turbines, and the great stress these speeds would set up in the commutators and windings of the generators.

When driven by turbines, they are usually coupled together by gears. For example a 360 R. P. M. generator can be driven by a 3600 R. P. M. turbine, through speed reducing gears with a ratio of 10 to 1.

Fig. 5 shows a small D. C. generator driven by a vertical steam engine. Note the flywheel used to maintain even speed and voltage, and also note the commutator and brushes which are in plain view on this generator.

Fig. 6 shows a larger D. C. generator also driven by a steam engine; which, in this case, is of the horizontal type and is located behind the generator. Note the very large flywheel used on this machine, and also the commutator and brush rigging on the left.

Direct current is not much used where the energy must be transmitted over distances more than one-half mile to a mile, as it requires high voltage to transmit large amounts of power over longer distances; and it is usually not practical to operate D. C. generators at voltages above 750.

Where large amounts of power are used in a compact area, such as in a large factory, in mines, steel mills, or densely built up business section of cities, D. C. finds its greatest use.

Where direct current is desired for use at a considerable distance from the location of the power plant, alternating current may be used to transmit the energy at high voltage, to a substation in which a motor generator set is used to produce D. C.

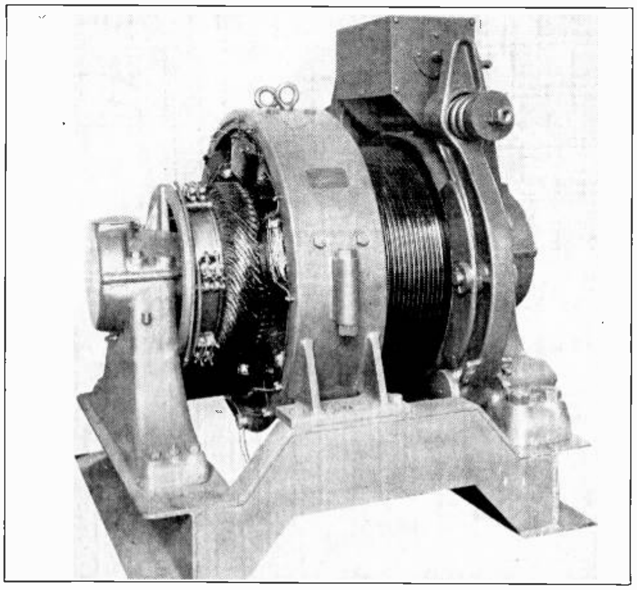


Fig. 4. This photo shows a D. C. elevator motor with the magnetic brake on the right end of the cable drum.

Fig. 7 shows a motor generator of this type, consisting of an A. C. motor on the left, driving a D. C. generator on the right. In this case the two machines are coupled directly together on the same shaft.

Other common uses for Direct Current are for electro-plating, electrolytic metal refining, battery charging, operation of electro-magnets, farm lighting plants, and automotive equipment.

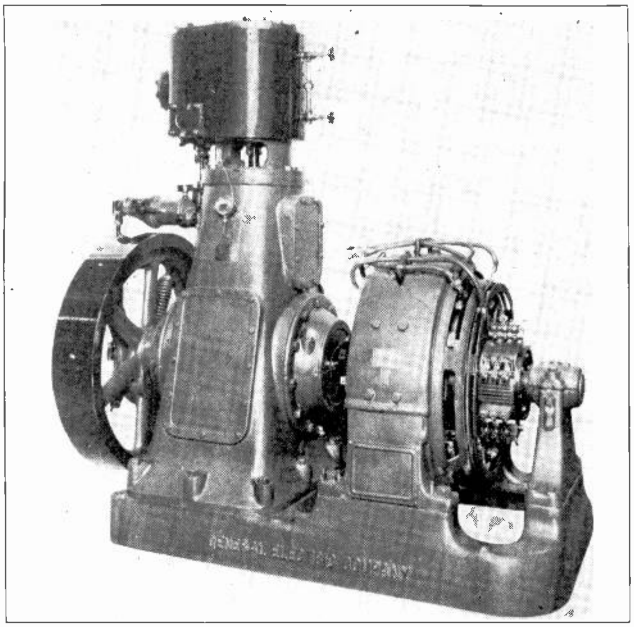


Fig. 5. Small engine-driven D. C. generators of the above type are used in a great number of privately owned power plants.

D. C. generators for electro-plating and electrolytic refining, are made to produce low voltages, from 6 to 25 volts, and very heavy current of several thousand amperes on the larger machines.

Garages use thousands of small motor generators, to produce D. C. for battery charging; and stores and plants using large fleets of electric trucks, charge their batteries with D. C. from larger charging generators.

Train lighting with the thousands of batteries and generators for this work is another extensive field for D. C. equipment.

Many thousands of D. C. farm lighting plants are in use throughout this country, supplying direct current at either 32 volts or 110 volts for light and power on the farms.

Powerful electro-magnets requiring direct current for their operation, are used by the thousands to speed up the handling of iron and steel materials in industrial plants, railway shops, etc. Fig. 8 shows a large magnet of this type which is used for lifting kegs of nails and bolts. This illustration also shows how the magnetism acts through the wooden kegs, proving what we have learned in an earlier section—that magnetism cannot be insulated.

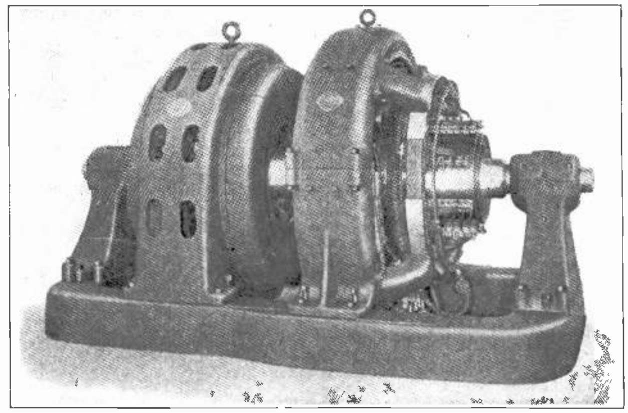


Fig. 7. Motor generator sets of the above type are very extensively used for changing A. C. to D. C. The D. C. generator is shown on the right and is driven by the A. C. motor on the left.

The automotive field is an enormous user of direct current equipment. Each modern automobile has a complete little power plant of its own, consisting of its D. C. generator, series D. C. starting motor, battery, lights, ignition coil, horn, etc. Many millions of D. C. generators and motors are in use on cars and trucks in this country alone. Fig. 9 shows a common type of 8 volt, shunt-wound, D. C. automotive generator.

Many powerful busses also use gas electric drive, having a gasoline engine to drive a D. C. generator, which in turn supplies current to D. C. motors geared to the axles. This form of drive provides

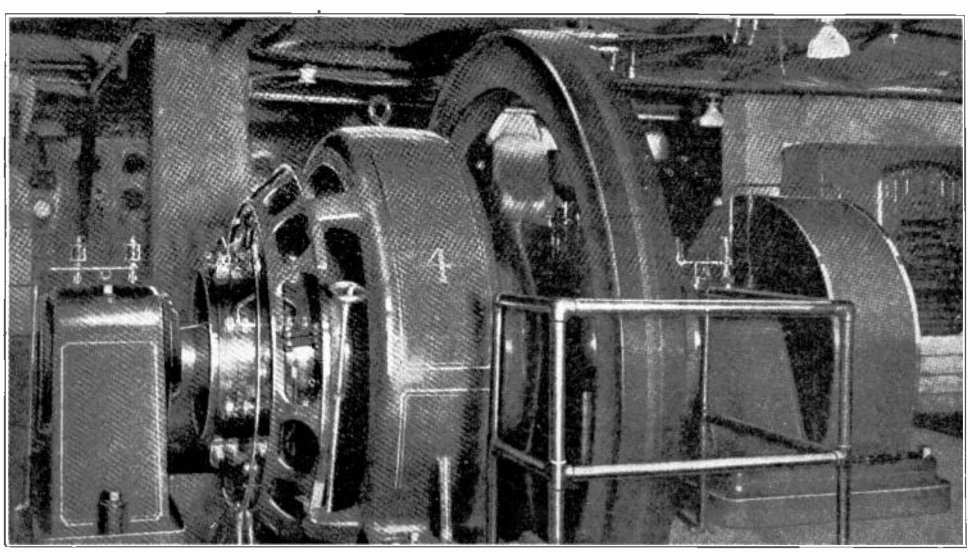


Fig. 6. This photo shows a large D. C. generator such as used in a great many industrial and railway power plants. Note the large fly wheel which is used to keep the speed of the generator even and "smooth out" the pulsations produced by the strokes of the engine.

Fig. 8. Direct current is used to operate powerful electro-magnets of the above type for handling metal materials in industrial plants, warehouses, foundries, and iron yards. Note the manner in which these kegs of bolts are lifted by the magnet, even though the wooden heads of the kegs are between the magnet and the metal to be lifted. In plants where the principal supply of electricity is alternating current small motor generators are often used to supply the direct current for magnets of this type.

smoother starting and stopping, greater hill climbing ability, higher speeds on level roads and eliminates gear shifting. Diesel-Electric trains also use D. C. generators and motors.

With this great variety of uses for direct current and D. C. machines you can readily see the value of making a thorough study of the equipment and principles covered in this section. The opportunities open to a trained man are certain to be much greater if he has a good knowledge of the operation, care and testing of direct current machines of all common types.

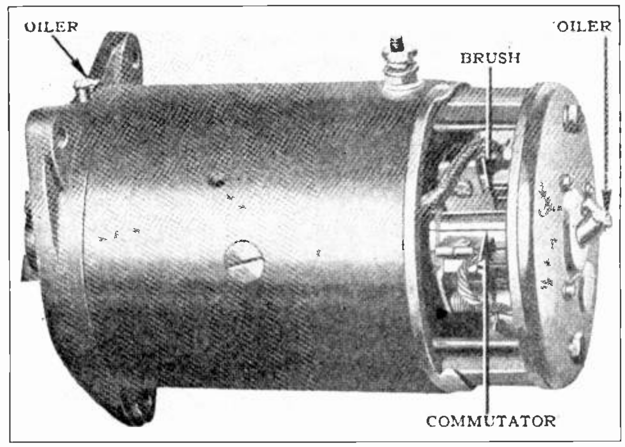


Fig. 9. Direct current generators of the above type are used by the millions on automobiles.

D. C. GENERATORS

It has already been stated in an earlier section, that D. C. generators and motors are almost exactly alike in their mechanical construction, and that in many cases the same machine can be used either as a motor or a generator, with only slight changes in the field connections, brush adjustment, etc. This is a very good point to keep in mind while studying the following material, as many of the points covered on construction, operation, load ratings, temperatures, etc., will apply to either a motor or a generator.

1. GENERATOR RATINGS

D. C. generators are always rated in kilowatts, a unit of electric power with which you are already familiar. It will be well to recall at this point, however, that one kilowatt is equal to 1000 watts, and approximately 1.34 h. p. You will also recall that the watts or kilowatts consumed in any circuit are equal to the product of the volts and amperes. Therefore, with a machine of any given voltage, the greater the load in K. W., the greater will be the load in amperes of current carried by the windings of that machine.

The K. W. rating of a D. C. generator is the power load that it will carry continuously without excessive heating, sparking, or internal voltage drop.

If a load greater than a machine is designed or rated for is placed upon it for an extended period, it will probably give trouble due to one of the three causes mentioned; and if the overload is very great and left on too long it will cause the armature winding to burn out.

Nearly all generators are designed to be able to carry some overload for short periods without injury to the machine. This is usually from 15 to 25 per cent, for periods not longer than an hour or so.

2. OPERATING TEMPERATURES

The safe temperature rises in electrical machinery are determined by the temperatures the insulating materials will withstand without damage. All other materials in the machine are metals which may be subjected to quite high temperatures without much damage.

Of course the higher the temperature of the copper windings the greater their resistance will be, and the higher will be the losses due to voltage drop in the machine.

Ordinary combustible insulations such as silk, cotton, and paper, should never be subjected to temperatures higher than 212° F. (or 100° C). Mica, asbestos, and other non-combustible insulations may be subjected to temperatures as high as 257° F., or 125° C.

In establishing temperature rise ratings for electrical machinery, it is assumed that the temperature in the rooms where the machines are installed will never be over 104° F. or 40° C. This gives, for the ordinary insulations, a permissable rise of 212 — 104, or 108° F. or 60° C. For non-combustible insulations the permissable rise is 257 — 104, or 153° F. or 85° C.

Ordinary generators and motors are usually guaranteed by the manufacturers to operate continuously at full load, without exceeding a temperature rise of 35° C., 40° C., or 50° C., as the case may be.

The temperatures of machines can be checked by placing small thermometers in between, or close to, the ends of their windings. A good general rule to remember, is that if the hand can be held on the frame of the machine near the windings without great discomfort from the heat, the windings are not dangerously hot.

3. GENERATOR SPEEDS

The speeds at which generators are operated depends upon their size, type of design, and method of drive. The speed is of course rated in R. P. M. (revolution per min.) but another expression commonly used in referring to the rotating armatures of electrical machines is the **Peripheral Speed**. This refers to the travelling speed of the outside or circumference of the rotating element, and this surface is commonly known as the **Periphery**. This speed is expressed in feet per second or feet per minute.

The centrifugal force exerted on the armature conductors or commutator bars depends on the peripheral speed of the armature or commutator. This speed, of course, depends on the R. P. M., and the diameter of the rotating part.

The larger the armature, the farther one of its conductors will travel in each revolution. When a coil of a bi-polar, (two pole) machine makes one revolution, it will have passed through 360 actual or mechanical degrees and 360 electrical degrees. But a coil of a six pole machine will only have to rotate 120 mechanical degrees to pass two poles, and through 360 electrical degrees.

So we find that with the same flux per pole in the larger machine as in the two pole one, the same E. M. F. can be generated at a much lower speed with the multipolar machine.

Small generators of two or four poles and for belt drive, have long armatures of small diameter and may be operated at speeds from 120 to 1800 R. P. M. Larger machines for slower speed drive by direct connection to the shafts of low speed reciprocating engines, may have as many as 24 or more field poles, and operate at speeds of 60 to 600 R. P. M. Armatures for these lower speed machines are made shorter in length and much larger in diameter, so their conductors cut through the field flux at high speeds, even though the R. P. M. of the armature is low.

The peripheral speeds of armatures not only determine the voltage induced and the stresses on the coils and commutator bars, but also determine the wear on brushes and the type of brushes needed, as will be explained later.

4. TYPES OF DRIVES

Belt driven generators are not much used in large plants any more because of possible belt slippage, and the danger of high speed belts. A number of older plants and many small ones use belt driven machines, and with fairly satisfactory results if the proper belts and pulleys are used.

One advantage of small belt driven generators is that they can be designed for high speeds and are much lower in cost.

The engine type generator with the large diameter, slow-speed armature, direct connected to the engine shaft, is more commonly used. Steam engines are a very desirable form of prime mover for generators, because of their high efficiency, simple operation, and because they can be operated on the ordinary steam pressures.

Steam turbines are used to drive D. C. generators in plants where space is limited, because they are so small and compact.

Water wheels are used for prime movers where convenient water power is available. Generators for water wheel drive may be either low or high speed type, according to the water pressure and type of water wheel used.

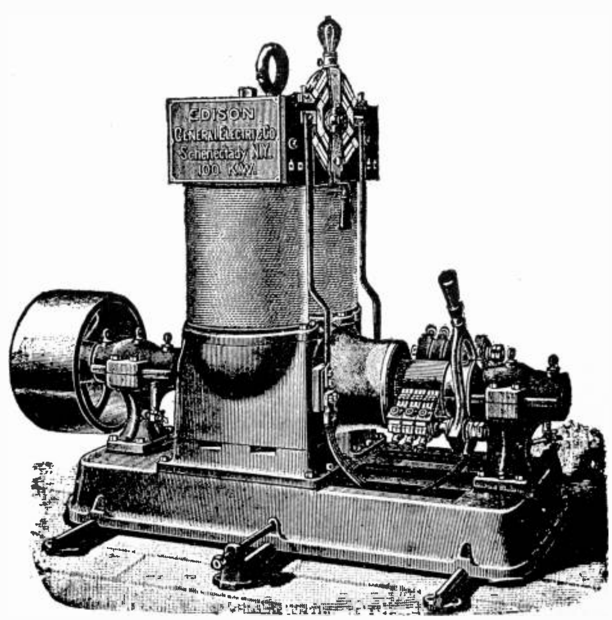


Fig. 10. An early type of D. C. generator developed by Thomas Edison. Note the construction of the field magnets of this machine.

5. MECHANICAL CONSTRUCTION OF D. C. GENERATORS

We have already learned that a generator is a device used to convert mechanical energy into electrical energy. We also know that the principal parts of a D. C. generator are its field frame, field poles, armature, commutator, brushes, bearings, etc.

The purpose of the field poles is to supply a strong magnetic field or flux, through which the armature conductors are rotated to generate the voltage in them.

D. C. generators were the first type commercially used, and the early types were very simply constructed with two large field poles in the shape of a huge bipolar electro-magnet. The armature was located between the lower ends of these magnets, as shown in Fig. 10. This figure shows one of the early types of Edison generators of 100 K. W. size.

6. FIELD FRAMES

Modern generators and motors have their field poles mounted in a circular frame, as shown in Fig. 11. This figure shows a two-pole field frame with the two large poles mounted on the inside of the frame. The field coils can be plainly seen on the poles.

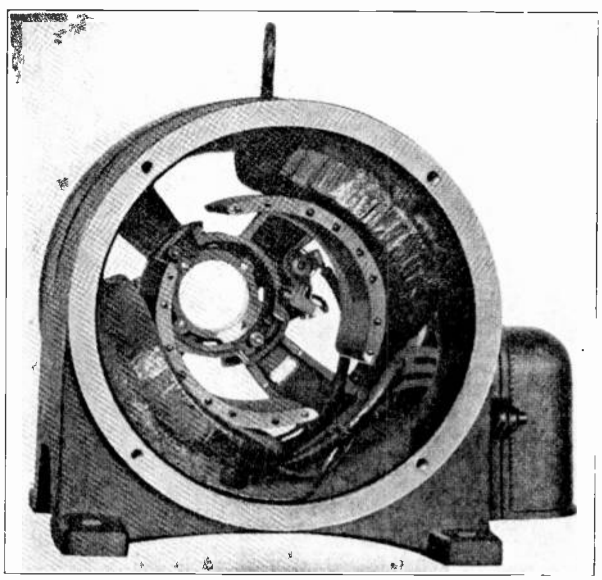


Fig. 11. Field frame of a modern generator or motor. Field coils located on the poles set up powerful magnetic flux in which the armature rotates.

The circular frame, in addition to providing a support for the field poles, also provides a complete closed path of magnetic material for the flux circuit between the poles. For this reason the frames are usually made of soft iron.

For the smaller and medium sized machines, they are generally cast in one piece with feet or extensions for bolting to a base. The inner surface is usually machined smooth where the poles are bolted to it, or in some cases the poles are cast as a part of the frame. The ends of the frame are machined to allow the bearing brackets to fit properly.

The frames for larger generators are usually cast in two pieces for more convenient handling during installation and repairs. They can be split either horizontally or vertically. Fig. 12 shows a frame of this type for an eight-pole machine. Note where the halves of the frame are joined together and bolted at each side.

7. FIELD POLES

There may be any equal number of field poles in a generator or motor frame, according to its size and speed. These poles are made of soft iron to keep the magnetic reluctance as low as possible.

The poles can be cast as a part of the frame on smaller machines, but are usually bolted into the larger frames. It is very important that they should fit tight to the frame to prevent unnecessary air gaps and reluctance in the magnetic circuit.

The ends of the poles which are next to the armature are usually curved and flared out into what are called **Pole Shoes** or **Faces.** This provides a more even distribution of the field flux over the armature core and conductors. These pole shoes are generally machined to produce an even air gap between them and the armature core.

Pole shoes are often made of laminated strips to keep down the induced eddy currents from the flux of the moving armature conductors. These laminated pole shoes are then bolted to the field poles. The machine in Fig. 11 has laminated pole shoes of this type.

In some large machines the entire field poles are often laminated for the same reason as the pole shoes are.

The field coils may be wound with round or square copper wire or with thin copper strip or

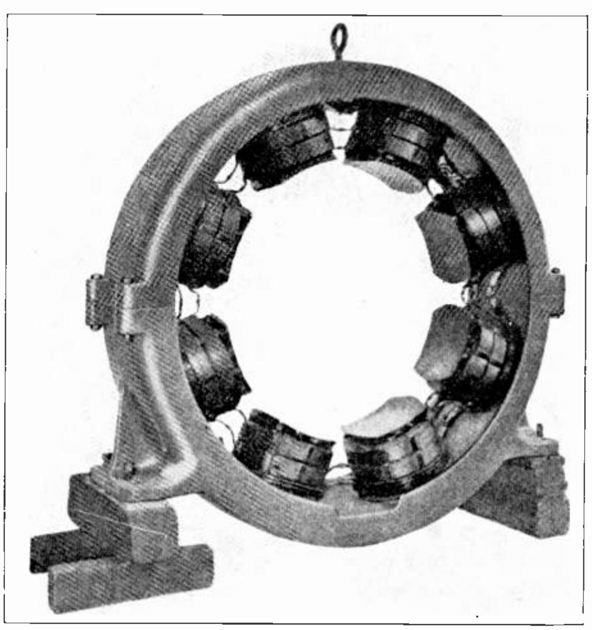


Fig. 12. Field frame for an eight-pole D. C. generator. Note the manner in which the frame is built in two sections for convenience when installing and making repairs.

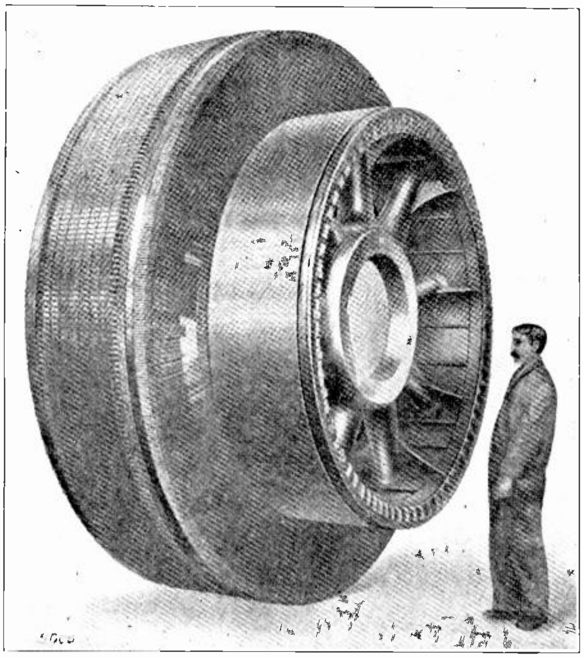


Fig. 13. This large armature shows the size to which D. C. generators can be built. An armature of this size would develop several thousand horsepower.

ribbon. These coils are connected to produce alternate north and south poles around the frame. In Fig. 12 the connections between the field coils can be noted.

8. ARMATURES

We have already learned a great deal about this very important part of D. C. machines, as armature construction and winding were thoroughly covered in the preceding section. A few of the points that are particularly good to keep in mind throughout the study of D. C. motors and generators will be briefly reviewed here.

The function of the armature, we know, is to carry the rotating conductors in its slots and move these swiftly through the magnetic flux of the field, in order to generate the voltage in them.

Armature cores are made of thin laminations of soft iron which are partially insulated from each other either by a thin coating of oxide which is formed on their surface when they are being heat treated or by a thin layer of insulating varnish. This laminated construction prevents to a great extent the eddy currents which would otherwise be induced in the core as it revolves through the field flux.

The very soft iron and steel in armature cores and its excellent magnetic properties also greatly reduce hysteresis loss. Also remember that the number of turns per coil and the method of connecting these coils will determine the voltage that is induced in a generator armature, or the counter-voltage in a motor armature.

Fig. 13 shows a very large armature of a D. C. generator with the commutator on the right. This view clearly shows the coils in the slots, and the long risers which extend from the commutator bars up to these coil ends. This armature and commutator give some idea of the size to which the larger D. C. generators and motors can be built.

9. COMMUTATORS

A commutator, we already know, is a device used to rectify or change the alternating E. M. F. which is induced in the armature, to a direct E. M. F. or voltage in the external circuit. A commutator might also be called a sort of rotating switch which quickly reverses the connections of the armature coils to the external circuit as these coils pass from one pole to the next.

The manner in which the commutators are constructed of forged copper bars which are insulated from each other by mica segments, was covered in a preceding article under D. C. armatures.

Figs. 14 and 15 show two excellent views of commutators of slightly different types. The smaller one in Fig. 14 is held together by the ring nut shown on the right, while the larger one is known as a "bolted type" commutator, and has bolts which draw the V-rings tightly into the grooves in the bars.

10. BRUSHES

The brushes slide on the commutator bars and deliver the current from a generator winding to the line; or, in the case of a motor, supply the current from the line to the winding. Most of these brushes are made of a mixture of carbon and graphite molded into blocks of the proper size. While this material is of fairly high resistance, the very short length of the brushes doesn't introduce enough resistance in the circuit to create much loss. The

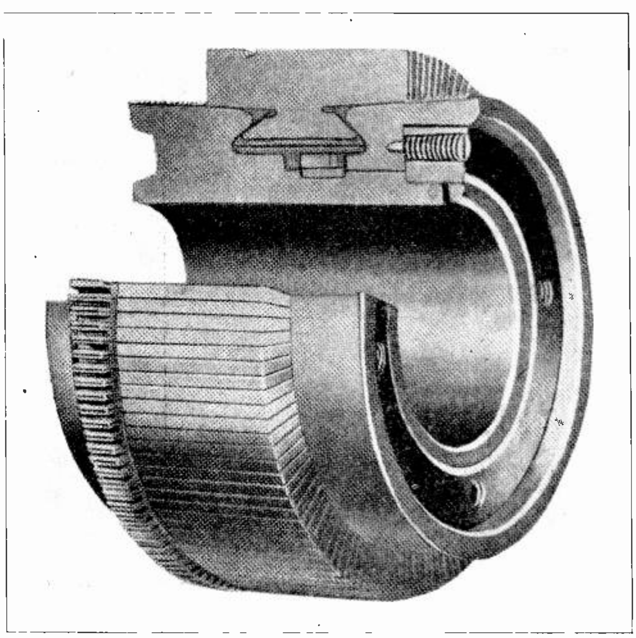


Fig. 14. The above photo shows an excellent sectional view of a commutator for a D. C. machine.

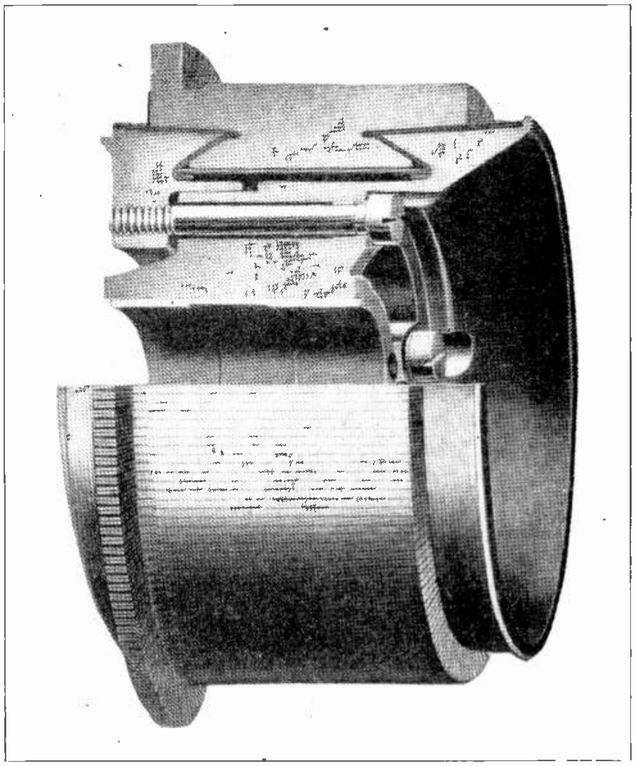


Fig. 15. This view shows another type of commutator in which the bars are held in place by bolts that are used to draw the clamping rings tight.

properties of the carbon and graphite tend to keep the commutator clean and brightly polished as the brushes slide on its surface. Some resistance in the brush material is an advantage, as it tends to prevent severe sparking during the period the commutator bars are short circuited. This will be explained in a later section on brushes.

Brushes must be of the proper size and material to carry, without undue heat, the full load currents of either a generator or motor. The carrying capacity of the brushes is a figure generally set by the manufacturers to indicate the number of amperes the brush will carry per square inch of cross-sectional area. This figure takes into account the heat due to overloads, friction, short circuit currents in the coils, voltage drop at the contact, and the heat produced by sparking.

Fig. 16 shows two common types of generator brushes to which are attached **Pig Tails** of soft stranded copper. These copper pig-tails are used for making a secure connection to carry the current from the brush to the holder and line.

11. BRUSH HOLDERS

Brushes are held firmly in the correct **position** with relation to the commutator by placing them in brush holders. The brush holders in common commercial use today may be classed under three general types, called **Box Type, Clamp Type,** and **Reaction Type.**

The box type holder was one of the first to be developed and used, while the clamp type has been developed in two forms known as the "swivel" and "parallel" motion types. Fig. 17 shows sketches of these several types of brush holders. The upper views in each case show the holders assembled on round studs, while the lower views show them bolted to rectangular studs.

A brush holder, in addition to providing a box or clamp to hold the brush in place, also has springs to hold the brush against the commutator surface and under the proper tension. Fig. 18 shows a box-type brush holder and the springs which apply the tension on the brush, and the view on the right shows this brush holder from the opposite side, mounted in the rocker ring. The requirements of good brush holders are as follows:

1. To provide means for carrying the current from the brush to the holder stud, either with a flexible copper connection or by direct contact between the brush and the holder. This must be accomplished without undue heating or sparking between the brush and holder, as this would result in a rapid burning and damage to the holders.
2. To provide means for accurately adjusting the brush on the commutator or ring.
3. To hold the brush firmly at the proper angle.
4. To permit free and quick movement of the brush in order that it may follow any uneven surface of the commutator or ring.

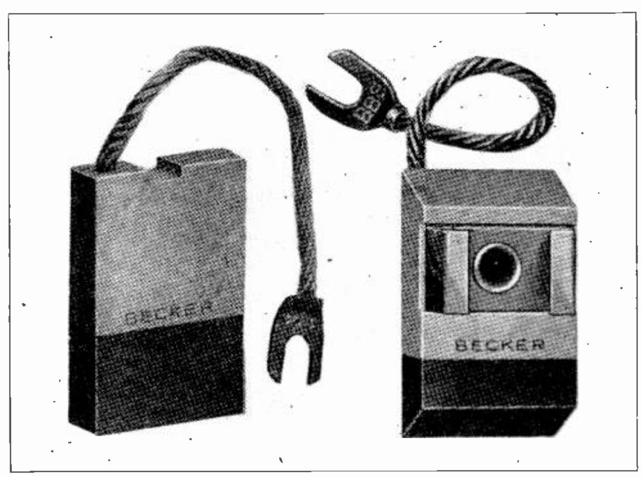


Fig. 16. Two common types of carbon brushes used for D. C. machines. Note the flexible copper leads used for connecting them to the brush holders.

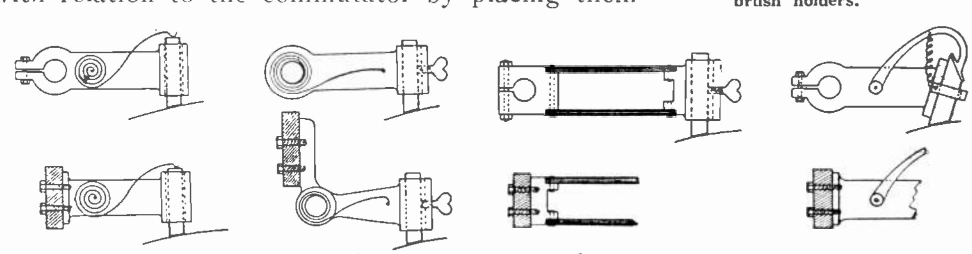


Fig. 17. The sketches on the left show several common types of brush holders. At "A" are two views of box-type holders. "B" and "C" are known as clamp-type holders; while "D" is a brush holder of the reaction-type.

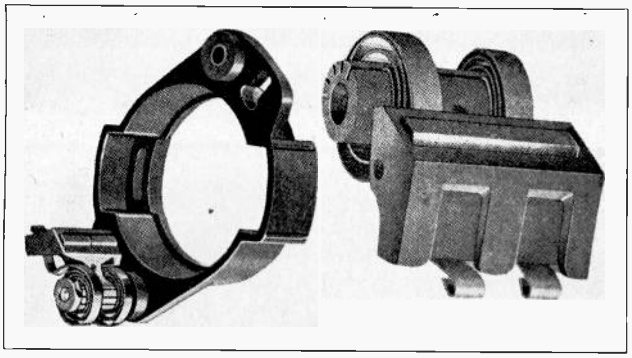


Fig. 18. Above are shown two box-type brush holders. The one at the left is simply attached to its holder stud sleeve and springs, while the one at the right is mounted on the holder stud which is fastened in a brush rocker arm.

5. To provide a tension spring of such length or shape that the tension on the worn brush will be very little less than that on a new brush.

6. To have a brush hammer so constructed that it will bear directly on the top of the brush and not give a side push either when the brush is full length or nearly worn out.

Fig. 19. shows a brush holder of the **Reaction Type,** in which the brush is held securely between the commutator surface and the **Brush Hammer** shown on the top in this view. The spring used with this brush holder is a coiled steel wire and can be seen on the back of the holder near the hammer hinge.

Brush holders are generally mounted or attached to a **Rocker Ring** by means of holder studs, as shown in Fig. 20. The holders can usually be adjusted on these studs both sidewise and up and down, to provide the proper spacing and tension. The purpose of the rocker frame or ring is to allow

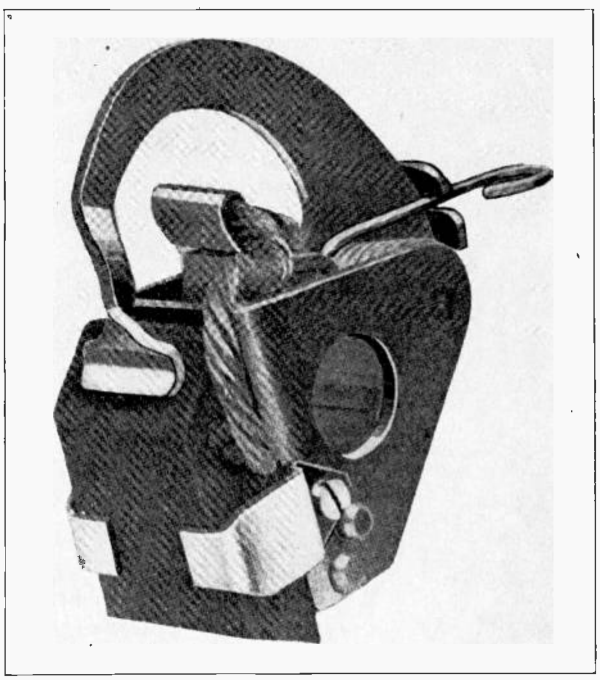


Fig. 19. Reaction-type brush holders keep the brush in place by the pressure of a "brush hammer", as shown on top of the brush in this view.

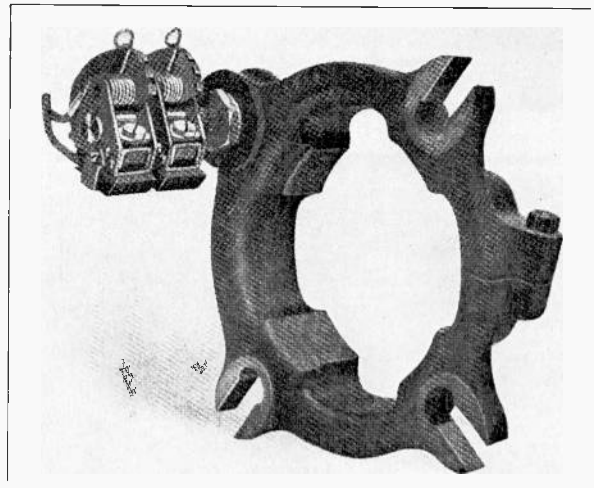


Fig. 20. Above are shown two brushes in their holders which are mounted on a brush rocker arm for a four-pole machine. Note the coil springs by which the brush tension on the commutator can be adjusted.

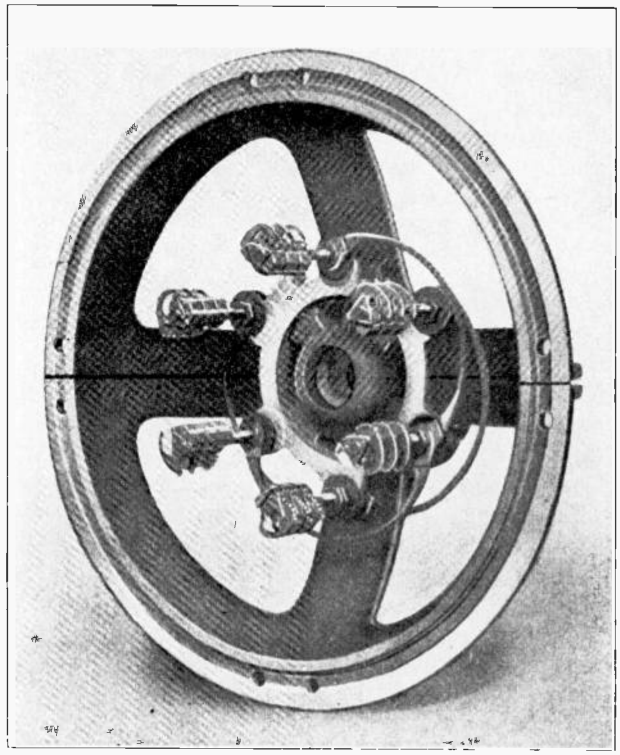


Fig. 21. This view shows a complete set of brushes and holders mounted on the rocker arm, which in turn is fastened in the end bracket of the machine.

the entire group of brushes to be rotated through a small arc, so their position can be adjusted for varying current loads on the machine. This is often necessary on machines that do not have interpoles — as will be explained later.

Frequently there are two or more brushes mounted on each stud, as several small brushes are more flexible and will fit themselves to uneven commutator surfaces much better than one large brush. The brush holder studs are, of course, insulated from the rocker frames by means of fibre washers and bushings.

Fig. 21 shows six sets of brushes mounted on the brush holder studs and rocker frame, which in turn is mounted in the end bracket of the machine.

12. BEARINGS

As previously mentioned, the bearings of motors and generators are to support the armature properly centered between the field poles and to allow it to rotate freely when the machine is in operation. These bearings are mounted in bearing brackets and held firmly at the ends of the machine; or, in some cases, they may be mounted in pedestals which are separate from the field frame.

These bearings are of two common types, called sleeve bearings and ball bearings. Roller bearings are also used in some cases. Sleeve bearings are made of babbit metal on the medium and larger sized machines, while bronze is used for very small, high-speed machines. Bearing metal must always be of a different grade than that in the shaft, because two similar metals will rapidly wear away or eat into each other when they are rubbed together.

Sleeve-type bearings are commonly oiled by oil rings or chains which rotate in the oil well and carry a small amount of oil up on top of the shaft continuously while it is rotating. In other cases, on smaller machines, the oil is fed to the shaft by a cotton wick. Ball and roller bearings are lubricated with a light grade of grease.

A more thorough study of bearings will be given in a later section. The principal point to remember at this time in connection with bearings is the importance of keeping all bearings properly lubricated with clean oil. There should always be enough oil to be sure that the bearings are receiving it; but never oil them excessively and thus cause an overflow which may run into the winding and damage their insulation or get on the commutator and destroy its clean, bright surface.

OPERATING PRINCIPLES OF D. C. GENERATORS

We have learned that the E. M. F. or voltage in a generator is produced by electro-magnetic induction when the conductors of the armature are rotated through the lines of force of the field.

We also know that the amount of voltage produced depends on the number of lines of force which are cut per second. This in turn depends on the strength of the field, the speed of armature rotation, and the number of turns or coils in series between brushes.

The voltage that will be produced by a generator can be calculated by the formula:

$$E = \frac{P \times \phi p \times Cr \times RPM}{10^8 \times 60 \times M.}$$

in which:

P = No. of field poles
ϕp = Total useful flux per pole
Cr = Total No. of inductors on armature
10^8 = 100,000,000 lines of flux to be cut per sec. by one conductor
60 = 60 sec. per min.
M = No. of parallel conducting paths between the + and — brushes.

For example, suppose we have a machine with 4 poles and with 200 armature inductors (conductors) in four parallel circuits between the brushes. The machine runs at 1200 R.P.M., and we will assume that the useful flux per pole is 3,000,000 lines.

$$\text{Then } E = \frac{4 \times 3{,}000{,}000 \times 200 \times 1200}{100{,}000{,}000 \times 60 \times 4}\text{, or 120 volts.}$$

You may not need to use this formula often, but it serves to show what the voltage of generators depends upon in their design and also to illustrate the factors of greatest importance in regulating the voltage of a generator.

It is an easy matter to determine the direction of induced voltage in the conductors of a generator by the use of **Fleming's Right Hand Rule**, which has been previously stated and explained.

The rule is one that you will have a great deal of use for in connection with generators, so we will repeat it here.

Place the first finger, thumb and remaining fingers of the right hand all at right angles to each other. (See Fig. 22). **Let the first finger point in the direction of magnetic flux from the field poles, the thumb in the direction of conductor rotation, and the remaining fingers will indicate the direction of induced voltage.**

This rule can be used either with diagrams or at the machine to quickly determine the direction of induced voltage in any conductor, where the direction of conductor movement and field polarity are known.

13. MAGNETIC CIRCUIT IN A GENERATOR

The number of conductors in the armature of a generator usually remains unchanged once it is built, and while the speed can be varied somewhat, the machine is generally operated at about the speed for which it is designed. So we find that the voltage adjustment or variation during the operation of a generator will depend largely upon the field strength. It would be well, therefore, to consider more in detail some of the factors upon which this field strength depends, and also the methods by which it can be varied.

Every generator or motor has what is called a **Magnetic Circuit.** This is the path followed by the flux of its field poles through the poles themselves, and through the armature core, and field frame — as shown in Fig. 23.

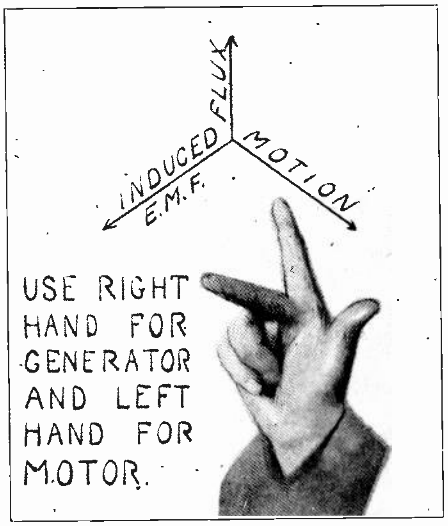


Fig. 22. This figure shows a method of holding the fingers to use the right-hand rule for determining direction of induced voltage in generators.

There are always as many magnetic circuits in a generator as it has poles. That is, a two-pole generator will have two magnetic circuits. A four-pole generator four magnetic circuits, etc. These magnetic paths must be continuous and will complete themselves through air unless iron or steel is provided. It is advisable, therefore, to have as much of the magnetic circuit through iron as possible, in order to reduce the reluctance of the circuit and increase the strength of the field.

The magnetic paths of commercial generators are completed through an all-iron or steel path, with the exception of the air gap between the armature core and field poles. If this air gap is increased it will weaken the strength of the field and reduce the generator voltage considerably.

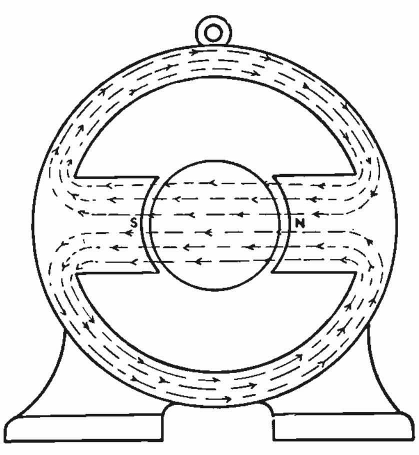


Fig. 23. The above diagram shows the magnetic circuit or path of the field flux in a simple two-pole machine.

Fig. 24 shows a sketch of a four-pole generator frame and the four magnetic circuits which it will have. It is very easy to determine the direction of flux at any pole of a generator if we know which ends of the pole are N. and S., and simply remember the rule that magnetic flux always travels from a north to a south pole in the external circuit. Examining Fig. 24 again, we find that the flux from either north pole divides and half of it goes to each of the south poles, then through the air gap and armature core which form the external circuit for the field poles. The internal circuit from the south pole back to the north pole is completed through the field frame. From this we see that each pair of field poles of a generator form a sort of horse-shoe magnet.

The area of the field poles and frame must be great enough to carry the flux without saturation. For highest efficiency, generators are operated at field densities considerably less than saturation, and generally at about 20,000 to 40,000 lines per sq. inch.

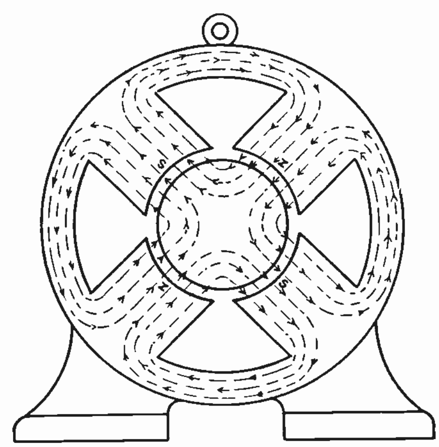


Fig. 24. Magnetic circuits in a four-pole machine. Note the direction of flux from N. to S. poles in the external circuit and from S. to N. poles in the internal circuit of the field.

14. FIELD EXCITATION

We know that the strong magnetic field of the poles in a generator is set up by direct current flowing through the coils on these iron poles. This current is called the **Field Exciting Current.** The strength of the field will, of course, depend on the number of turns in the field coils and the amount of current which is passed through them. So, by **controlling excitation current with a rheostat, we can readily adjust the strength of the field and the output voltage of the generator.**

Generators are classed as either **Separately Excited** or **Self-Excited,** according to the manner in which their coils obtain the exciting current.

A separately excited generator is one that has its field excited from some source other than its own armature. This source may be either a storage battery or another small D.C. generator. Alternating current cannot be used to excite the field poles of either a D.C. or A.C. generator. So alternators are practically always separately excited by current from storage batteries or D.C. generators. Separately excited D.C. generators are sometimes used for electro-plating machines and work of this type, and have their field coils wound for a certain voltage. This voltage may range from 6 to 25 for battery excitation; and from 110 to 220 when excited from another generator.

Fig. 25 shows a sketch of a simple two-pole D.C. generator which has its field separately excited from a storage battery. Note the field rheostat which is provided to vary the field current and the generator voltage.

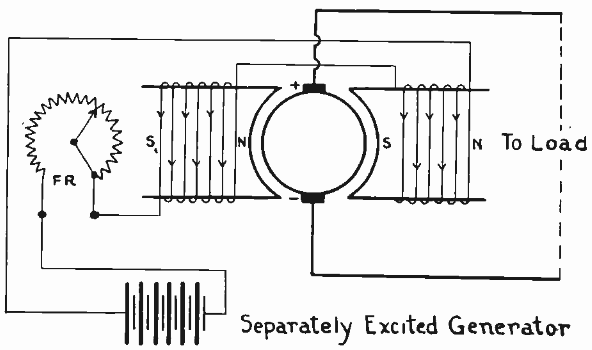


Fig. 25. This diagram shows a simple D. C. generator which has its field separately excited from a storage battery.

A self-excited generator is one that receives its field current from its own armature winding. Fig. 26 shows a sketch of a simple generator of this type. You will note that the field coils are connected across the positive and negative brushes of the armature in parallel with the line and load. The field will at all times receive a small amount of D. C. from the armature, whether there is any load connected to the line or not. Practically all commercial D.C. generators are self-excited.

15. BUILDING UP VOLTAGE IN A GENERATOR

With a separately excited generator, as soon as the circuit is closed from the source of direct current for the field, the field will be magnetized at full strength, and the generator voltage will build up immediately as soon as the machine goes up to full speed.

A self-excited generator must build up its voltage more gradually from the small amount of residual magnetism in the poles when the machine is started. You will recall that residual magnetism is the magnetism which remains in or is retained by the iron of the field poles even when their current is shut off. This residual magnetism, of course, produces only a very weak field.

When the machine is first started up and the armature conductors begin to cut this weak residual field, a very low voltage is generated in them. As the field is connected to the armature this first low voltage slightly increases the strength of the field. Then as the conductors cut through this slightly stronger field a little higher voltage is induced in them. This increases the field strength still more, which in turn builds up a greater voltage in the armature and further increases the field strength. This continues, and the strength of the field as well as the armature voltage keep on getting greater, until the point of **Saturation** is reached in the field poles.

The saturation point, you will remember, is when a magnetic circuit is carrying its maximum practical load of flux. When this point is reached it would require a considerable increase of current in the field coils to make even a small increase in the flux of the poles. So we find that self-excited generators build up their voltage gradually from residual magnetism as the machine comes up to speed.

Sometimes it may require a few seconds after the machine has reached full speed for its voltage to come up to normal value.

16. FAILURE TO BUILD UP VOLTAGE

With self-excited generators, it is, of course, necessary that the flux lines produced by the field coils be of the same polarity as the residual magnetism in the iron of the poles. Otherwise, the first low voltage applied to the field coils would tend to neutralize the residual magnetism and cause the generator to fail to build up its voltage. For this reason, self-excited generators will build up voltage only when rotated in the proper direction. Generators may, however, be made to build up voltage when rotated in the opposite direction by changing the field connections.

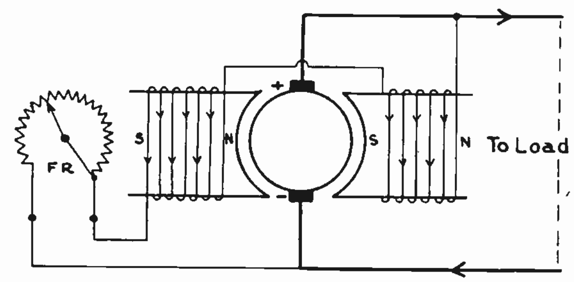


Fig. 26. This simple two-pole machine has its field coils self-excited by connection to its own armature brushes. Note the field rheostat at F. R., which is used to control the field strength.

After a generator has been idle for quite a period it sometimes loses its residual magnetism to such an extent that it will not build up voltage until it is first separately excited. Some of the causes of a generator failing to build up voltage are as follows: Weak or dead residual magnetism, low speed, poor brush-contact on the commutator, severe overloads, open field circuits, or high resistance connections.

Removing the cause of the trouble will usually start the machine generating, but if it does not a low voltage storage battery or some other source of direct current applied to the field coils momentarily and in the proper direction will generally cause the machine to promptly build up voltage again.

On some generators it is necessary to cut out part or all of the resistance of the field rheostat before the machines will build up voltage.

17. VOLTAGE ADJUSTMENT AND REGULATION

When a generator is running at normal speed, its voltage can be conveniently controlled and adjusted by means of the field rheostat, as shown in Figs. 25 and 26. On most D.C. generators this adjustment is made manually by the operator, putting resistance in or out of the field circuit by means of this rheostat. In some cases automatic voltage regulators are used to control this voltage according to the load on the machine. This automatic regulating device will be explained later.

The terms "control" and "adjustment" refer to changes made in the voltage by the operator or automatic device. The term "voltage regulation" refers to some change in the voltage which the machine makes of its own accord as the load is changed or varied. This change is inherent in the machine and is determined by its design and construction.

18. NEUTRAL PLANE

The neutral plane in a generator is that point between adjacent field poles at which the armature conductors are traveling parallel to the lines of force, and in a very weak field. Normally, when the generator is not carrying a load this neutral plane is half way between adjacent poles of opposite polarity, as shown in Fig. 27.

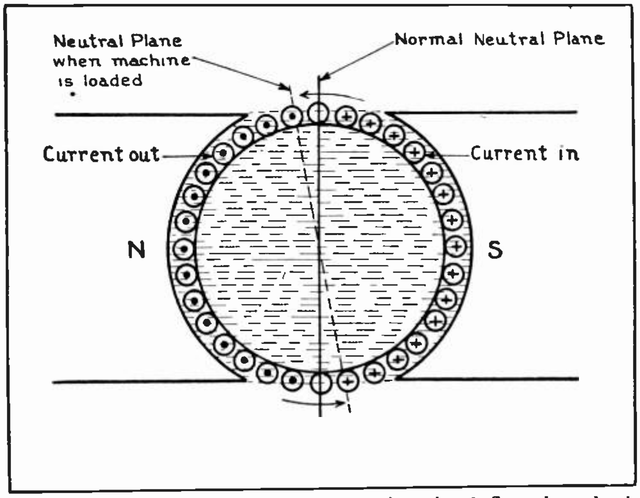


Fig. 27. This diagram shows the normal path of flux through the armature of the generator when the machine is not operating under load. Note the position of the normal neutral plane and also the position this plane takes when a machine is loaded.

When the conductors are passing through this point they do not generate any voltage, as they are not cutting across the lines of force. It is at this point that the commutator bars attached to the conductors usually pass under the brushes, where they are momentarily short circuited by the brushes. If the brushes were allowed to short circuit coils while they were passing through a strong flux under a pole, and generating appreciable voltage, it would cause very severe sparking at the brushes. So it is important that the brushes be adjusted properly for this neutral plane.

19. ARMATURE REACTION

In addition to the flux which is set up between the field poles from their coils and exciting current, there is also to be considered the flux around the armature conductors. When a load of any kind is connected to a generator and its voltage begins to send current out through the line and load, this current, of course, flows through the armature conductors of the generator as well.

The greater the load placed on the machine the greater will be the current in the armature conductors and the stronger will be the flux set up around them.

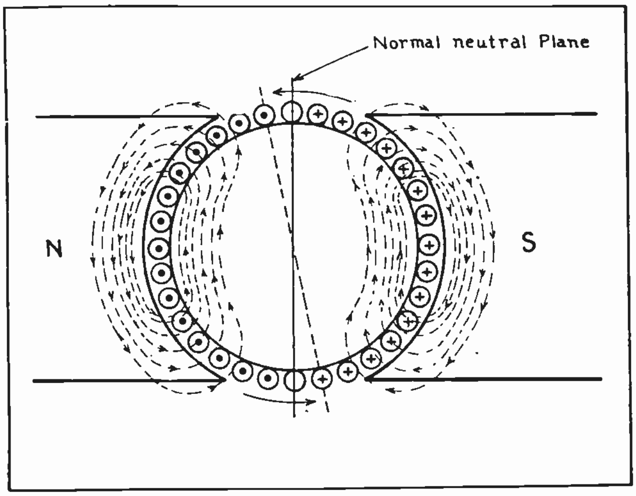


Fig. 28. This sketch shows the magnetic flux set up around the armature conductors of the simple two-pole machine when current is passing through them.

The armature flux is set up at right angles to the flux of the field poles, and therefore tends to distort the field flux out of its straight path between poles. This effect is known as **Armature Reaction.**

Fig. 28 shows the position of the armature flux as it would be when set up by current in the conductors, if there were no field flux to react with it. In actual operation, however, the armature and field flux of the generator are more or less mixed together or combined to produce the distorted field shown in Fig. 29. Here we see that the lines of force from the field poles have been shifted slightly out of their normal path and are crowded over toward the tips of the poles which lie in the direction of the rotation of the armature. This causes the field strength to be somewhat uneven over the pole faces, and more dense on the side toward which the armature is rotating.

You will also note that this distortion of the field has shifted the neutral plane, which must remain at right angles to the general path of the field flux.

As the armature flux depends on the amount of current through its conductors, it is evident that the greater the load on the machine, the greater

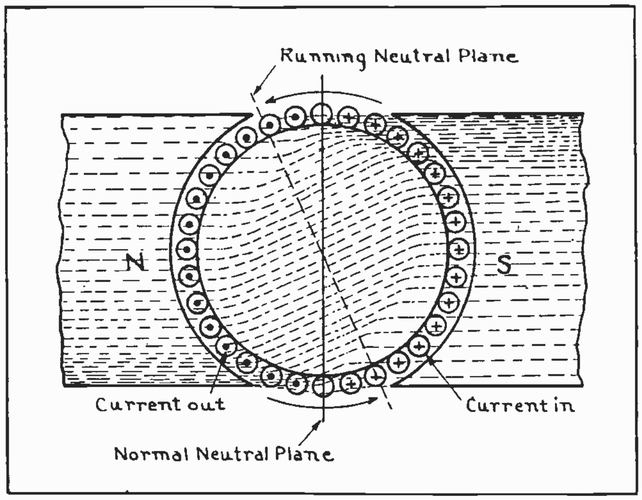


Fig. 29. This view shows the manner in which the magnetic lines of the field are distorted from their normal path by the effect of armature reaction. The neutral plane is shifted counter clockwise, or in the direction of rotation as shown by the dotted line.

will be the armature reaction and field distortion; and the farther the neutral plane will be shifted from its original position. So unless a generator is provided with some means of overcoming the effect of armature reaction, it will be necessary to shift the brushes with varying loads in order to obtain sparkless commutation.

Some machines are provided with **commutating poles or interpoles,** as they are sometimes called, which are placed between the main field-poles to neutralize this feature of armature reaction and thereby eliminate the necessity of shifting the brushes with changes of load. These poles and their operation will be more fully explained later.

The tendency of the armature flux to distort the field flux constantly exerts a force in the opposite direction of rotation and this force is what requires more power of the prime mover to drive the generator when its load is increased.

20. ARMATURE RESISTANCE AND I. R. LOSS

All armature windings offer some resistance to the flow of the load current through them. While this resistance is very low and usually only a fraction of an ohm, it nevertheless causes a certain amount of voltage drop in the internal circuit of the armature. In other words, a certain small amount of the generated voltage is used to force the load current through the resistance of the armature winding. The greater the load on a generator, the greater will be the voltage drop through the armature.

As we know, this voltage drop is always proportional to the product of the amperes and ohms; and for this reason it is often referred to as **I. R. Drop.**

We can also determine the watts lost in an armature, or converted into heat because of its resistance, by squaring the current and multiplying that by the resistance, according to the watts law formula. Therefore, $I^2 \times R$ will equal the watts lost in an armature due to its resistance. In which:

I = the load current

R = the resistance of the armature only.

This armature resistance can be measured with instruments connected to the commutator bars at the brush locations; or it can be calculated, if we know the size of the wire, the length of the turns in the coils, and the number of paths in parallel in the armature.

21. VOLTAGE DROP IN BRUSHES AND LINES

There is also a certain amount of voltage drop at the brushes of a generator which is due to the resistance of the brushes themselves and also the resistance of the contact between the brushes and commutator. This resistance is also very low and will cause a voltage drop of only about one or two volts on ordinary machines under normal load.

In addition to the voltage drop encountered in the generator, we also have the drop in the line which leads from the generator to the devices which use the current produced by the generator.

Knowing that the voltage drop in both the line, or external circuit, and the generator internal circuit will vary with the amount of load in amperes, we can see the desirability and need of some voltage adjustment or regulation at the generator, to keep the voltage constant at the devices using the energy.

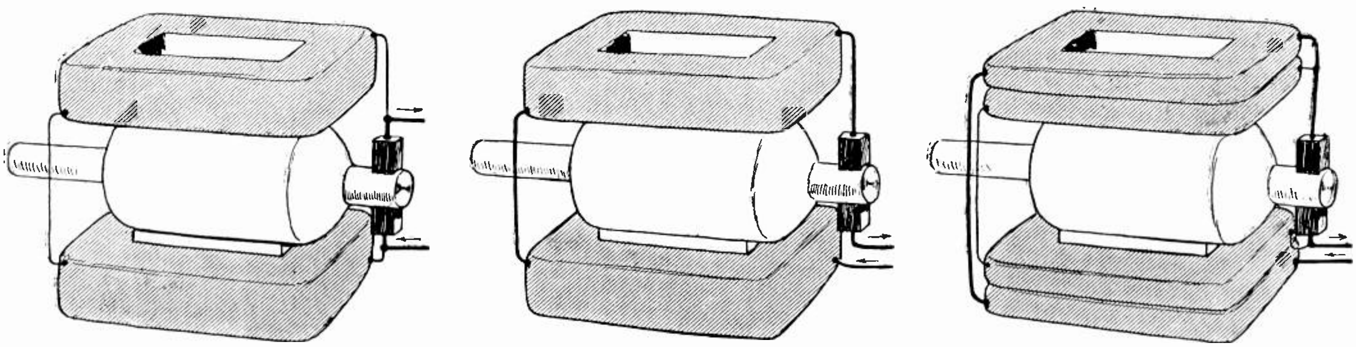
GENERAL TYPES OF D. C. GENERATORS

Direct current generators can be divided into several classes, according to their field construction and connections. They are called respectively: **Shunt Generators, Series Generators, and Compound Generators.**

The shunt generator has its field coils connected in shunt or parallel with the armature, as shown in Fig. 30-A. Shunt field coils consist of a great many turns of small wire and have sufficient resistance so that they can be permanently connected across the brushes and have full armature voltage applied to them at all times during operation. The current through these coils is, therefore, determined by their resistance and the voltage of the armature.

Series generators have their field coils connected in series with the armature, as shown in Fig. 30-B; so they carry the full load current. Such coils must, of course, be wound with heavy wire in order to carry this current and they usually consist of only a very few turns.

Compound generators are those which have both a shunt and series field winding, as shown in Fig. 30-C.



A B C

Fig. 30. "A" shows the connections of the field coils for a shunt generator. Note that they are connected in parallel with the brushes and the armature. "B" shows the connection of the field coils for a series machine. "C" illustrates the connection of the field coils for a compound generator. Note that at "C" the shunt coils next to the armature are connected in parallel with the brushes while the series coils on the outside are connected in series with the brushes.

Each of these machines has certain characteristics which are particularly desirable for certain classes of work, as will be explained in detail in the following paragraphs.

22. SHUNT GENERATORS

Fig. 31 is a simple sketch showing the method of connecting the field winding of a shunt generator in parallel with its armature. The field rheostat, F.R., is connected in series with the shunt field winding to regulate the field strength, as previously explained.

It is well to note at this point that, in various electrical diagrams, coils of windings are commonly represented by the turns or loops shown for the shunt field at "F", while resistance wires or coils are commonly shown by zigzag lines such as those used for the rheostat at "F.R."

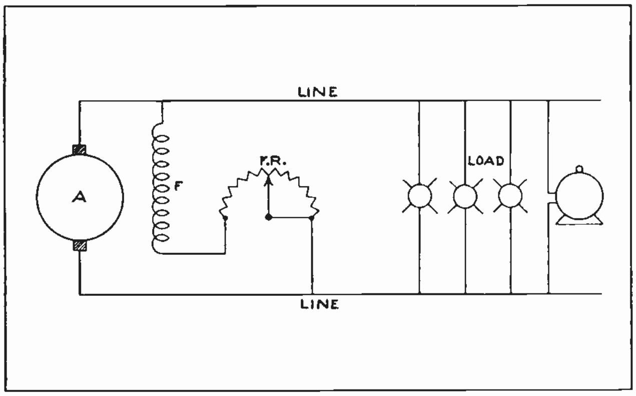


Fig. 31. This diagram shows the connections of a shunt generator. The shunt field winding "F" is connected in series with the field rheostat and then across the brushes. Note that this field winding is also in parallel with the load on the line.

Fig. 32 shows the connections of a shunt generator as they would appear on the machine itself. By comparing this diagram with the one in Fig. 31 and tracing the circuits of the field and armatures, you will find they are connected the same in each case.

The shunt generator, being a self-excited machine, will start to build up its voltage from residual magnetism as soon as the armature commences to rotate. Then, as the armature develops a small amount of voltage, this sends some current through the field, increasing the lines of force and building up the voltage to full value, as previously explained. However, if there is a heavy load connected to the line the shunt generator may refuse to build up its voltage, as the heavy load current flowing thru the armature causes a voltage drop thru the armature and brush resistance and reduces the terminal or output voltage of the armature. This reduces the voltage supplied to the field and may weaken the field enough to prevent the generator from building up voltage.

23. VOLTAGE CHARACTERISTICS OF SHUNT GENERATORS

The voltage of the shunt generator will vary inversely as the load due to the same reason mentioned in the preceding article. Increasing the load causes increased voltage drop in the armature circuit thus reducing the voltage applied to the field. This reduces the field strength and thereby reduces the generator voltage.

If the load on a shunt generator is suddenly increased, the voltage drop may be quite noticeable; while, if the load is almost entirely removed, the voltage may rise considerably. Thus we see that the voltage regulation of a shunt generator is very poor, because it doesn't inherently regulate or maintain its voltage at a constant value.

The voltage may be maintained fairly constant by adjusting the field rheostat, provided the load variations are not too frequent and too great.

Shunt generators are, therefore, not adapted to heavy power work but they may be used for incandescent lighting or other constant potential devices where the load variations are not too severe.

Shunt generators are difficult to operate in parallel because they don't divide the load equally between them. Due to these disadvantages shunt generators are very seldom installed in new plants nowadays, as compound generators are much more satisfactory for most purposes.

Fig. 33 shows a voltage curve for a shunt generator and illustrates the manner in which the voltage of these machines varies inversely with the load. You will note that at no load the voltage of the

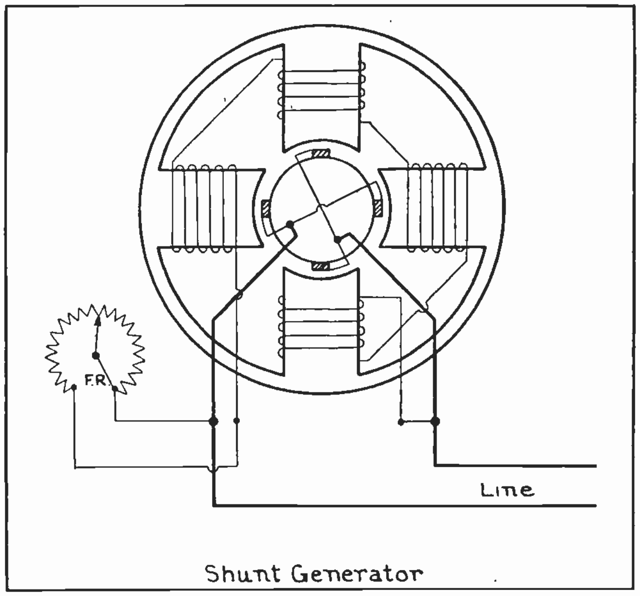


Fig. 32. This sketch shows the wiring and connections of the brushes and field coils for a four-pole, shunt generator.

generator is normal or maximum, while as the load in kilowatts increases the generator voltage gradually falls off to a lower and lower value.

24. SERIES GENERATORS

These machines have their field coils connected in series with the armature and the load, as shown in Fig. 34. The field winding is usually made of very heavy wire or strip copper, so that it will carry the full load current without overheating.

By referring to Fig. 34 we can see that with no load connected to the line, it would be impossible for any current to flow through the series field and therefore the generator couldn't build up voltage. So, in order for a series generator to build

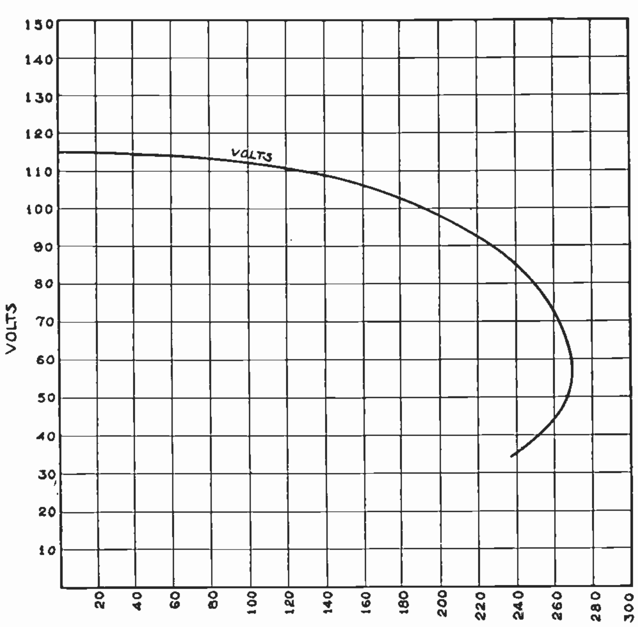


Fig. 33. This curve illustrates the voltage characteristic of a shunt generator. Note how the voltage drops as the load in kilowatts is increased. Full load in this case is 240 amperes.

up voltage when it is started, we must have some load connected to the line circuit.

25. VOLTAGE CHARACTERISTIC OF SERIES GENERATORS

The greater the load connected to such a generator, the heavier will be the current flowing through the field winding and the stronger the field flux. This causes the voltage of a series generator to vary directly with the load; or to increase as the load is increased and decrease as the load decreases. This, you will note, is exactly the opposite characteristic to that of a shunt generator.

As most electrical equipment is to be operated on constant voltage and is connected to the line in parallel, series generators are not used for ordinary power purposes or for incandescent lighting. Their principal use has been in connection with series arc lights for street lighting and a number of series generators are still used for this purpose.

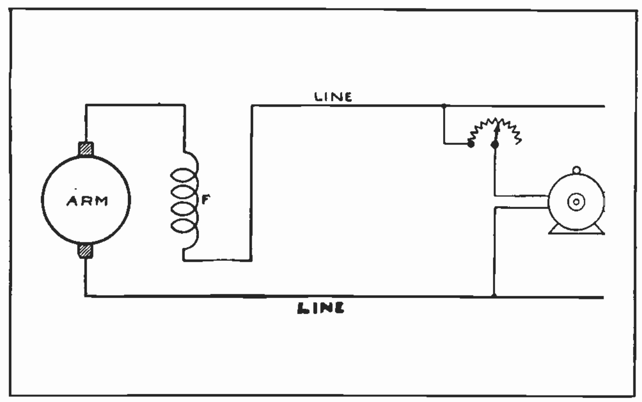


Fig. 34. This sketch shows the connections of a series generator. The series field at "F" is connected in series with the armature and the line. Note that no current could flow through this field if there was no load connected to the line.

With a load of this kind, the current must always remain at the same value for the series lamps and, therefore, the generator field and voltage will remain fairly constant. You can readily see that a series generator would be entirely impractical for ordinary power and light circuits, because, if the load is decreased by disconnecting some of the devices, the voltage on the rest will drop way below normal.

26. SERIES FIELD SHUNTS

Fig. 35 shows a curve illustrating the voltage regulation of a series generator. The voltage of such machines can be adjusted by the use of a low-resistance shunt connected in parallel with the series field coils, as shown in Fig. 36. This figure shows the connections of a series generator as they would appear on the machine. By tracing the circuit you will find that the field coils are connected in series with the armature and load.

The purpose of the shunt is to divide the load current, allowing part of it to flow through the series field and the rest through the shunt. By varying the resistance of this shunt, we can cause

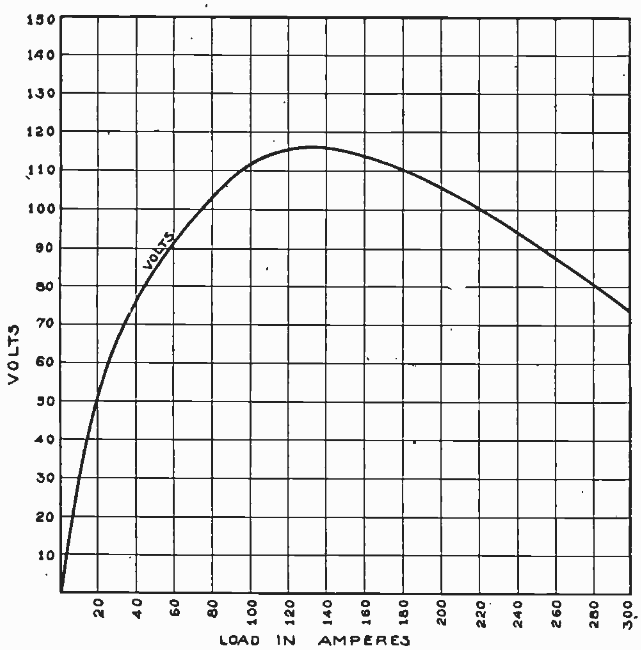


Fig. 35. This curve shows the voltage characteristic of a series generator. Note that the voltage increases rapidly as the load on the machine is increased up to about full load. Full load in this case is 125 amperes.

more or less of the total load current to flow through it, thus either weakening or strengthening the series field.

These shunts are generally made of very low resistance material, such as copper ribbon or strips of metal alloy with higher resistance than copper, in order to make them short in length and compact in size.

By referring again to the curve in Fig. 35, you can see that the voltage regulation of a series generator is also very poor.

27. COMPOUND GENERATORS

The fields of a compound generator are composed of both shunt and series windings, the two separate

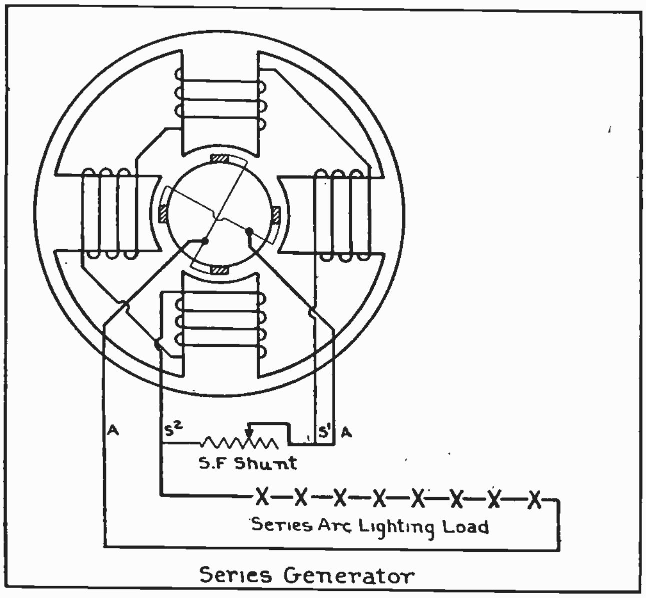


Fig. 36. Connections of brushes and field coils of a four-pole, series generator.

coils being placed on each pole. Fig. 37 shows the connections of both the series and shunt fields of a compound generator.

The shunt field is connected in parallel with the armature and therefore it maintains a fairly constant strength. The series field, being in series with the armature and load, will have its strength varied as the load varies. These machines will therefore have some of the characteristics of both shunt and series generators.

We have found that the shunt generator tends to decrease its voltage as the load increases and that the series generator increases its voltage with increases of load. Therefore, by designing a compound generator with the proper proportions of shunt and series fields, we can build a machine that will maintain almost constant voltage with any reasonable variations in load.

The shunt field winding of a compound generator is usually the main winding and produces by far the greater portion of the field flux. The series field windings usually consist of just a few turns, or enough to strengthen the field to compensate for the voltage drop in the armature and brushes as the load increases.

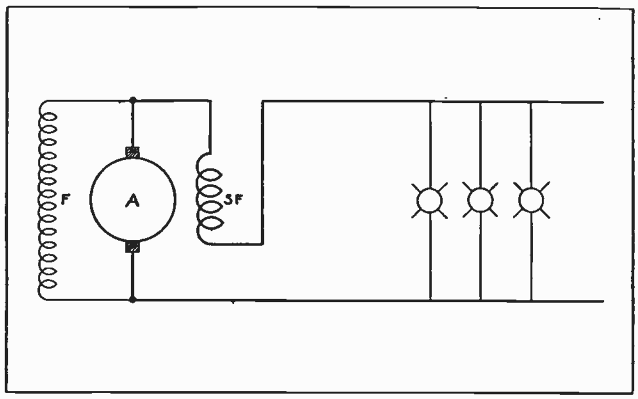


Fig. 37. This sketch shows the connections of a compound generator. The shunt field is connected across the brushes. The series field is connected in series with the line.

Compound generators can have the shunt field strength adjusted by a rheostat in series with the winding, and may also have a shunt in parallel with the series field for its adjustment. The series field shunt on these machines, however, is not generally used for making frequent adjustments in their voltage, but is intended for establishing the proper adjustment between the series and shunt field strengths when the generators are placed in operation.

The variation in the strength of the series field, which compensates for the voltage drop with varying load, makes it unnecessary to use the field rheostat with these machines, as is done with shunt generators.

Fig. 38 shows the complete connections for the armature and fields of a compound generator. You will note that the series winding is composed of just a few turns of very heavy wire on each pole and is in series with the armature and line. The shunt winding is composed of a far greater number of turns of small wire and is connected in parallel with the armature brushes.

By referring back to Fig. 12, you will note the series coils wound on the poles over or outside of the shunt winding, which is wound next to the pole cores.

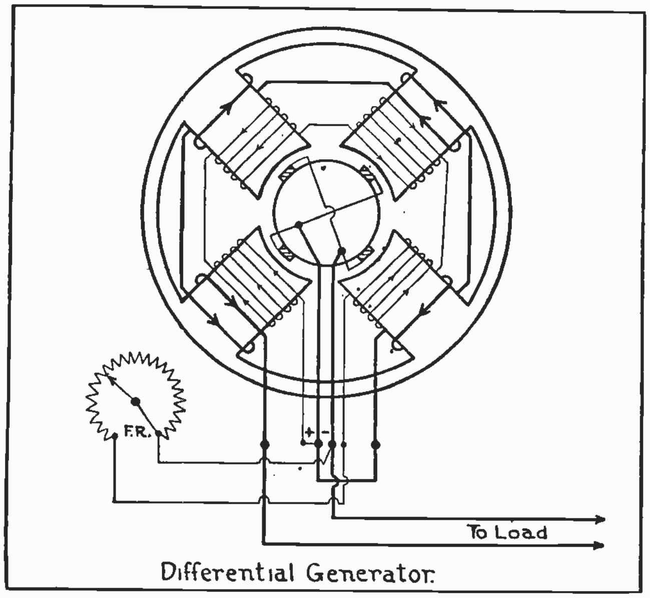


Fig. 38. Connections of brushes and field coils for a four-pole, cumulative compound generator. Note that the direction of current through the series field winding is the same as that through the shunt coils.

28. CUMULATIVE AND DIFFERENTIAL COMPOUND GENERATORS

In the type of compound generator which we have just described the series coils are wound in the same direction as the shunt coils, so their flux will aid and strengthen that of the shunt field. They are therefore known as **Cumulative Compound machines.** This name comes from the fact that the two windings both work together, or add their fluxes, to build up the total cumulative field.

Some compound generators have the series fields wound in the opposite direction, so that their flux opposes that of the shunt field. Such machines are known as **Differential Compound** generators. Their uses will be explained later.

29. FLAT COMPOUND GENERATORS. VOLTAGE CHARACTERISTICS

When a compound generator has just enough of series field to compensate for the voltage drop in its own armature and brushes, and to maintain a nearly constant voltage from no load to full load on the generator, it is known as a **Flat Compound** machine.

The voltage regulation of such a machine is very good, as it automatically maintains almost constant voltage with all normal load variations. Such machines are very commonly used for supplying current to general power and light circuits where the load is not located too far from the generator and the line drop is small. Fig. 39 shows the voltage curve of a flat compound generator at F.

30. OVER COMPOUND GENERATORS. VOLTAGE CHARACTERISTICS

Where the load is located some distance from the generator or power plant and the line drop is sufficient to cause considerable reduction of voltage at the current-consuming devices when the load is heavy, the generators are commonly equipped with series field windings large enough to compensate for this line drop as well as their own armature and brush voltage drop. Such machines are called **Over Compound** generators and are by far the most common type used in power work.

The voltage of an over compound generator will increase slightly at the generator terminals with every increase of load. These voltage increases are due to the greater number of turns in the series field winding. Every increase of load increases the current through these series turns, thereby strengthening the field enough to actually raise the voltage a little higher at full load than at no load.

This voltage increase at the generator terminals makes up for the additional voltage drop in the line when the load is increased. Therefore, if the series and shunt fields of such a machine are properly adjusted, it will maintain a very constant voltage on the equipment at the end of the line.

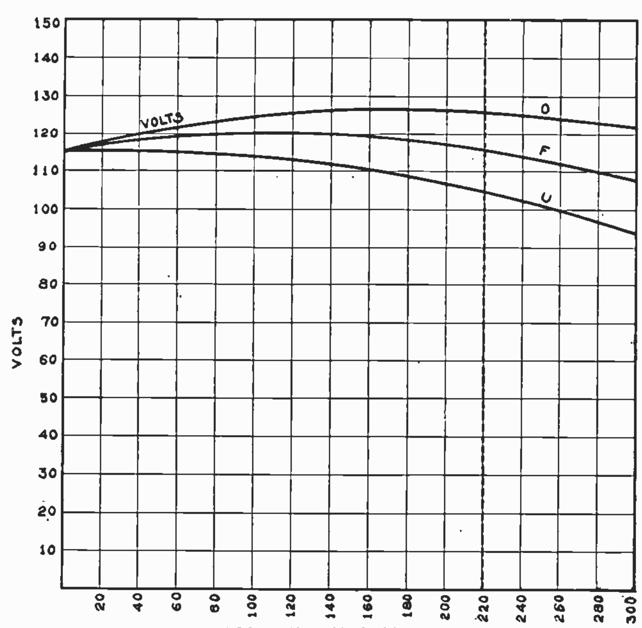


Fig. 39. These curves show the voltage characteristic of a flat compound generator at F, over compound at O, and under compound at U. Full load in this case is 220 amperes.

The adjustment of the shunt and series fields of these machines can be made with the usual shunt field rheostat and series field shunts.

The voltage regulation of an over compound generator is very good, and for ordinary power purposes they don't require frequent adjustment of the rheostat or any special voltage regulating equipment, because this regulation is inherent in the design and operation of the machine. Over compound generators are usually made and adjusted so that the terminal voltage will be from 4½% to 6% higher at full load than at no load.

31. DIFFERENTIAL COMPOUND GENERATORS

Any compound generator can be connected either cumulative or differential, by simply reversing the connections of the series field windings so that these coils will either aid or oppose the flux of the shunt field.

Compound generators are usually designed to operate cumulative unless otherwise ordered for special purposes.

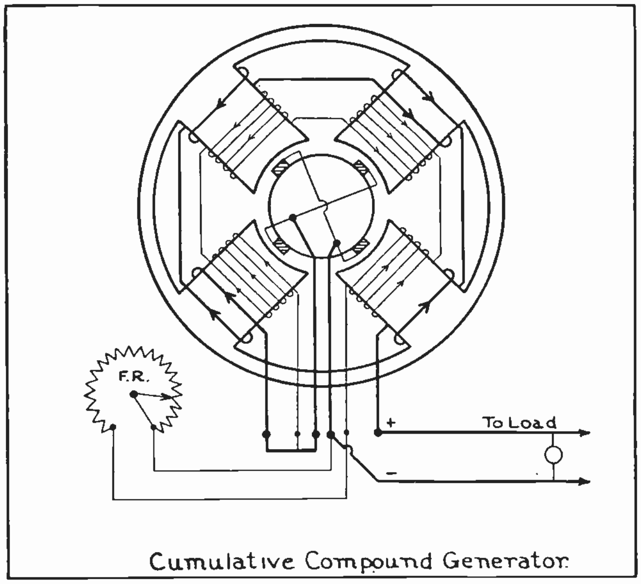


Fig. 40. Connections of brushes and field coils for a four-pole, differential, compound generator. Note that the direction of current through the series field coils is opposite to that in the shunt coils.

When the series field coils are connected differential, and so that their flux opposes that of the shunt field, each increase in the load on the machine will cause quite a decided voltage drop, as it increases the current in the differential winding and thereby weakens the field flux.

The voltage of these machines, therefore, will vary inversely with the load and considerably more than it varies with the shunt generator. The voltage regulation of differential compound generators may be classed as very poor, but they have advantages in certain classes of work.

For the generators used in welding, where sudden and severe overloads are placed on the machine in starting the arcs, or for any machines that have frequent severe overloads or the possibility of short

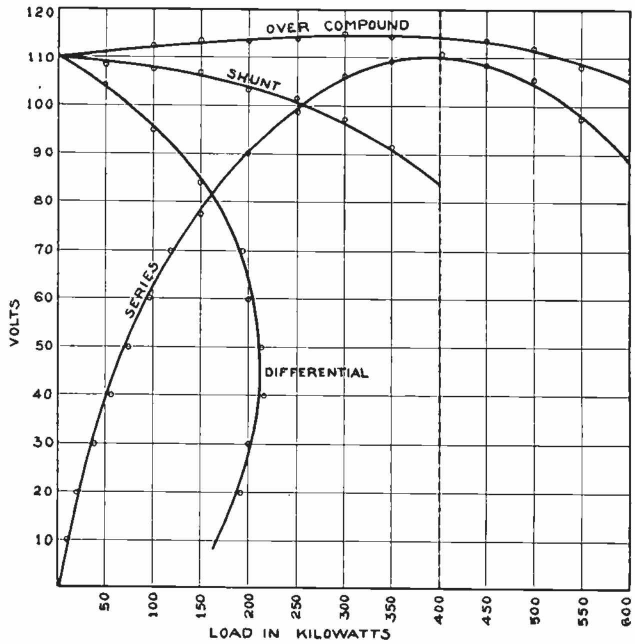


Fig. 41. This chart shows the curves of several types of generators all together so they can be easily compared.

circuits, the differential compound winding is a good protective feature.

When an overload is placed on the line, the additional current in the differential series coils tends to neutralize the shunt field flux and thereby reduces the generator voltage considerably. This also reduces the amount of current which will flow through the armature, and therefore protects it from overheating.

The shunt field winding of the differential generator should be the main field winding and determine the polarity of the pole. The series field should at no time determine the polarity of the poles, unless the shunt field circuit is open or except in case of a short circuit across the brushes.

Fig. 40 shows the connections of a differential compound generator. Note that the current flows in opposite directions in the shunt and series windings around the field poles.

Fig. 41 shows the curves for the several types of generators just described and provides a good opportunity to compare the voltage characteristics of shunt, series, and compound generators. Note how rapidly the voltage of the differential machine falls off as the kilowatt load increases.

It will be well to keep in mind the different voltage characteristics of these machines and the principles by which their voltage regulation is obtained, because you will encounter all types in various plants in the field. Therefore a knowledge of their field connections and adjustment, and the proper methods by which these connections can be changed to obtain different characteristics, will often be very valuable to you.

OPERATION OF D. C. GENERATORS

In commencing the study of the operation of generators, it will be well to first consider prime movers, or the device, used to drive the generators.

The term **Prime Mover** may apply to any form of mechanical power device, such as a steam engine, steam turbine, gas or oil engine, or water wheel. These devices, when used to drive electric generators, are designed to operate at a constant speed at all loads up to full load. They are usually equipped with governors which maintain this constant speed by allowing the correct amount of power in the form of steam, gas, or water to enter the prime mover, according to the variations of current load on the generator.

The prime mover should always be large enough to drive the generator when it is fully loaded, without any reduction in speed which would be noticeable in the generator voltage output.

It is not our purpose in this Electrical Reference Set to discuss in detail the design or operation of prime movers, although in a later section they will be covered to a greater extent with regard to their operation.

32. CALCULATION OF PROPER H.P. FOR PRIME MOVERS

To determine the proper size of engine or prime mover to drive a D.C. generator of a given rating in kilowatts, we can easily calculate the horse power by multiplying the number of kilowatts by 1.34.

You will recall that one h. p. is equal to 746 watts, and one kilowatt, or one thousand watts, is equal to 1.34 h. p.

Multiplying the kilowatt rating of the generator by 1.34 gives the horse power output of the machine. This horse power output can also be determined by the formula:

$$\text{H. P.} = \frac{E \times I}{746}$$

In which:

E = the generator voltage
I = the maximum current load rating
746 = the number of watts in one h. p.

In addition to the electrical horse power output of the generator, we must also consider its efficiency, or the loss which takes place in its windings and bearings.

If the efficiency of a generator is known to be 80%, the formula to determine the horse power required to drive it will be as follows:

$$\text{H. P.} = \frac{E \times I}{e \times 746}$$

In which:

e = the efficiency of the generator, expressed decimally.

We should also allow a certain amount for any overload that the generator is expected to carry. A convenient rule for determining the approximate horse power required to drive any generator, is to multiply the kilowatt rating of the machine by 1.5, which will usually allow enough extra power to make up for the loss in the generator.

For example, if we have a generator which is rated at 250 volts and 400 amperes, and this machine has an efficiency of 90%, we can determine the necessary horse power by the formula, as follows:

$$\text{H. P.} = \frac{250 \times 400}{.90 \times 746}, \text{ or } 148.94 \text{ h. p.}$$

The kilowatt rating of this same generator would be 100 KW, as can be proven by multiplying the volts by the amperes. So, if we simply multiply 100 × 1.5, according to our approximate rule, we find that 150 h. p. will be required. This is approximately the same figure as obtained by the use of the other **formula.**

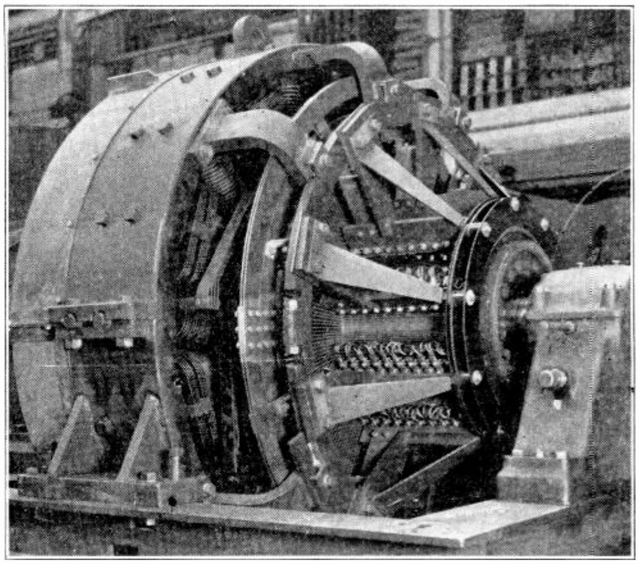


Fig. 41-A. This photo shows a large modern D. C. generator with a welded frame. The capacity of this generator is 1000 KW. What horse power will be required to drive it and satisfactorily maintain the speed when the generator is 10% overloaded? Assume the efficiency of the generator to be 93%.

If the generator has less than 90% efficiency and if it is known that the load will be up to the full capacity of the generator at pratically all times, and occasionally a little overload, then it is better to allow slightly greater horse power than in the problem just given.

Prime movers for the operation of generators should be equipped with governors which are quick enough in their response so that they do not allow the generator to slow up noticeably when additional load is applied.

There is generally some adjustment provided on these governors which can be used to set the prime mover to run the generator at the proper speed to maintain the proper voltage.

As the voltage of the generator depends upon its speed, we should keep in mind that its voltage can be adjusted by adjusting the governors or throttle of the prime mover.

33. INSPECTION BEFORE STARTING GENERATORS

When starting up a generator we should first make a thorough examination, to make sure that the prime mover and generator are both in proper running order. The oil wells should be examined to see that there is sufficient oil in all main bearings and that the oil rings are free to turn. Be careful, however, not to flood oil wells, because excess oil allowed to get into the windings of the generator is very damaging to the insulation, and may necessitate rewinding the machine.

On small and medium-sized machines only a little oil need be added from time to time, unless the oil wells leak. On large machines, where the armature is very heavy, forced lubrication is necessary to maintain the film of oil between the shaft and bearings. With these machines an oil pump is used to force oil to the bearings at a pressure of 20 to 30 lbs. per square inch to insure proper lubrication. Some bearings are also water cooled, having openings through the metal around the bearing for water to flow through and carry away excessive heat.

If there are auxiliaries of this kind, they should be carefully examined and checked before running the machine.

34. STARTING GENERATORS

Before starting up a generator it is usually best to see that the machine is entirely disconnected from the switchboard. This is not always necessary, but it is safest practice. Next start the prime mover and allow the generator armature to come gradually up to full speed. Never apply the power jerkily or irregularly.

Power generators are always rotated at their full speed when operating under load. When the machine is up to full speed **the voltage can be adjusted by means of the field rheostat which is connected in series with the shunt field.**

The machine voltage can be checked by means of the switchboard voltmeter, and it should be brought up to full operating voltage before any switches are closed to place load on the generator.

After the voltage is adjusted properly, the machine may be connected to the switchboard by means of the circuit breakers and switches. **Where circuit breakers are used they should always be closed first,** as they are overload devices and should be free to drop out in the event there is an overload or short circuit on the line.

After closing the circuit breaker the machine switch may be closed, completing the connection of the generator to the switchboard. As the switch is closed the operator should watch the ammeter and voltmeter to see that the load is normal and to make any further necessary adjustments with the field rheostat.

If the generator is operating in parallel with others, the ammeter will indicate whether or not it is carrying its proper share of the load. **The load on any generator should be frequently checked by means of an ammeter or wattmeter to see that the machine is not overloaded.**

The temperature of the machine windings and bearings should also be frequently observed in order to check any overheating before it becomes serious.

35. CARE OF GENERATORS DURING OPERATION

After the machine is running, the most important observations to be made frequently are to check the bearing oil and temperature, winding temperatures and ventilation, voltage of the machine as indicated by the volt meter, and the load in amperes shown by the ammeter. Commutator and brushes should also be observed to see that no unusual sparking or heating is occurring there.

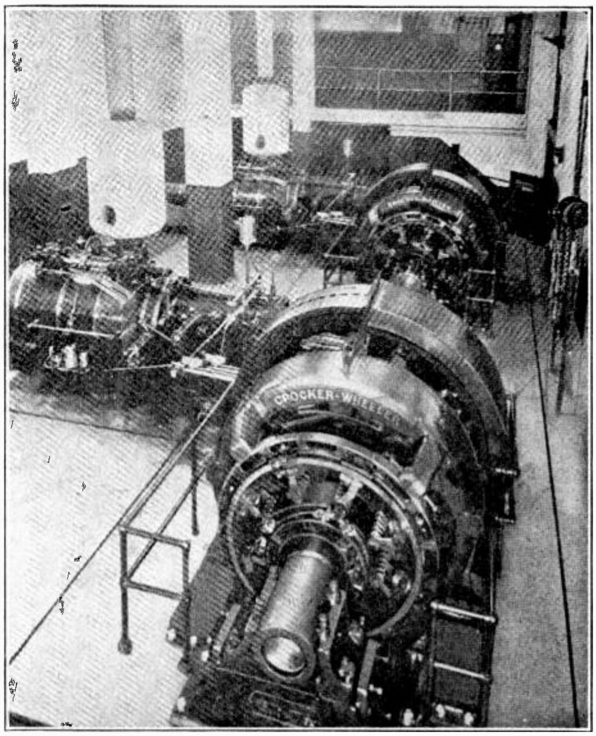


Fig. 41-B. This view shows two engine-driven D. C. generators in a power plant. Two or more machines of this type are commonly operated in parallel.

Commutators should be kept clean and free from dirt, oil, or grease at all times. Brushes should be kept properly fitted and renewed when necessary, and the commutator surface kept smooth and even for the best results.

All parts of an electric generator should be kept clean at all times as dust and oil tend to clog the ventilating spaces in the windings, destroying the value of the insulation, and also intefering with proper commutation.

The supply of ventilating air in the generator room should be frequently checked to see that it is not restricted, and that the temperature of the armature is not allowed to become too high. Moisture is very detrimental to the generator windings and water in or around the generator is very dangerous, unless confined in the proper pipes for such purposes as cooling bearings, etc. **Never use water to extinguish fire on any electrical equipment.**

36. PARALLELING D. C. GENERATORS

Where direct current is used in large quantities the power is usually furnished by several generators operating in parallel, rather than by one or two very large machines. The larger machines when operated at full load, are, of course, more efficient than smaller ones, but the use of several machines increases the flexibility and economy of operation in several ways.

If only one large generator is used and the load is small during a considerable part of the time, it is then necessary to operate the machine partly loaded. The efficiency of any generator is generally less when operating at less than full load, as they are designed to operate at highest efficiency when they are fully loaded or nearly so.

When several machines are used, the required number can be kept in operation to carry the existing load at any time. Then if the load is increased additional machines may be put in operation, or if it is decreased one or more machines may be shut down.

In a plant of this kind if any generator develops trouble it can be taken out of service for repairs, and its load carried by the remaining machines for a short period, if it doesn't overload them more than the amount for which they are designed.

37. IMPORTANT RULES FOR PARALLEL OPERATION

As we learned in the previous section on series and parallel circuits, when generators are connected in parallel their voltages will be the same as that of one machine. The current capacity of the number of generators in parallel, however, will be equal to the capacity of all of them, or the sum of their rated capacities in amperes.

To operate generators in parallel, **their voltages must be equal** and **their polarities must be alike.**

The positive leads of all machines must connect to the positive bus bar and the negative leads of all machines must connect to the negative bus bar. This is illustrated by the sketch in Fig. 42, which shows two D. C. generators arranged for parallel operation. You will note that if the switches are closed the positive brushes of both machines will connect to the positive bus bar, and the negative brushes are both connected to the negative bus bar.

The voltmeters connected to each machine can be used to check the voltage as the machine is brought up to speed, in order to be sure that it is equal to the voltage of the other machine which may already be running and connected to the bus. If the voltages are unequal to any great extent, the machine of higher voltage will force current backward through the one of lower voltage and tend to operate it as a motor.

It is, therefore, very important that the voltage be carefully checked before closing the switch which connects a generator in parallel with others.

If the polarity of one machine were reversed, then when they are connected together it would result in a dead short circuit with double voltage or the voltage of both machines applied in series.

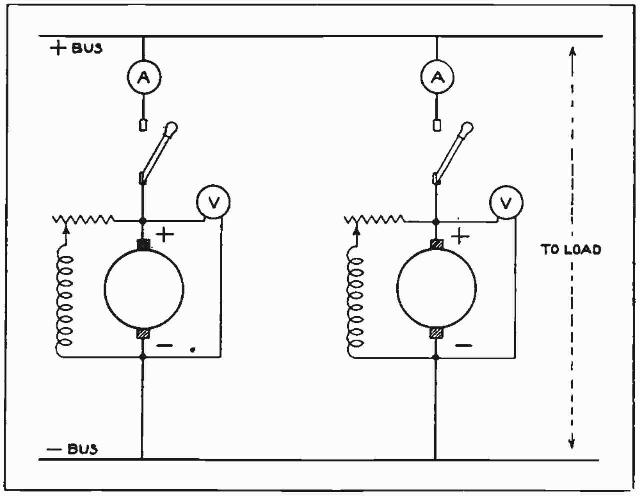


Fig. 42. This simple sketch shows a method of connecting two D. C. generators in parallel. Note the polarity of the generator brushes and bus bars.

Just try making a sketch similar to Fig. 42 and reverse the polarity of one generator and see what would happen. You will find that the positive of one machine feeds directly into the negative of the other, and so on around a complete short circuit.

The resistance of the machine windings, bus bars, ammeters and connections is so low that an enormous current would flow, until circuit breakers or fuses opened the circuit. If no such protective devices were provided, the windings would be burned out or possibly even thrown out of the slots, by the enormous magnetic stresses set up by the severe short circuit currents.

You can readily see that in such matters as these your training on electrical principles and circuits becomes of the greatest importance, as you should at all times know the results of your movements and operations in a power plant, and know the proper methods and precautions to follow.

38. CORRECTING WRONG POLARITY

If the polarity of a generator should build up wrong, or in the reverse direction, it will be indicated by the voltmeter reading in the wrong direction, and these meters should always be carefully observed when starting up machines.

Sometimes the generator will build up wrong polarity because its residual magnetism has reversed while the machine was shut down. Sometimes stopping and starting the machine again will bring it up in the right polarity if some load is connected on the circuit. If it doesn't, the polarity can be corrected by momentarily applying a low voltage source of direct current to the field coils and sending current through them in the proper direction.

In power plants where several D. C. generators are used, they are generally arranged so their fields can be connected to the bus bars, assuring proper excitation and polarity.

39. COMPOUND MACHINES BEST FOR GENERAL SERVICE

Shunt wound generators will operate quite satisfactorily in parallel on constant loads if their voltages are kept carefully adjusted to keep the load divided properly between them. If the voltage of one machine is allowed to rise or fall considerably above or below that of the others, it will cause the machine of lower voltage to motorize and draw excessive reverse current, and trip open the circuit breakers.

If the voltage of one machine falls only a little below that of the others, the back current may not be sufficient to open the breakers, but would be indicated by the ammeter of this machine reading in the reverse direction.

Shunt generators are not very often used in large power plants, because of their very poor voltage regulation and the considerable drop in their voltage when a heavy load is applied. A plain shunt generator can usually be changed for compound operation by simply adding a few turns of heavy wire around the field poles, and connecting them in series with the armature, with the right polarity to aid the shunt field flux.

The compound generator is best suited to most loads and circuits for power and lighting service and is the type generally used where machines are operated in parallel in D. C. power plants.

Series generators are not operated in parallel and in fact they are very little used, except for welders, test work or in older street lighting installations.

40. SIMILAR VOLTAGE CHARACTERISTICS NECESSARY FOR PARALLEL OPERATION

Compound generators can be readily paralleled if they are of the same design and voltage. They usually have similar electrical and voltage characteristics and should be made with the same compounding ratios. That is, the compounding effects of the machines must be equal even though they are of unequal size.

Machines of different kilowatt ratings can be satisfactorily operated in parallel, if they are made by the same manufacturer or of the same general design, so that each will tend to carry its own share of the load. If their compounding is properly proportioned, the voltage rise of each generator should be the same for a similar increase of load.

When a D. C. generator is operated in parallel with others and its voltage is increased, it will immediately start to carry a greater share of the current load. **We can, therefore, adjust the load on the various machines by increasing or decreasing their voltages the proper amount.**

41. TESTING AND ADJUSTING COMPOUNDING OF GENERATORS

The compounding effects of different generators can be tested or compared by separately loading in increasing amounts and observing their voltmeters. This can be done by connecting one of the machines to the switchboard, or to a special loading rheostat, and operating the machine under normal voltage. Then apply a certain amount of load to it and observe the voltmeter closely, to note the amount of increase in the voltage due to the compounding effect.

It will probably be well to check the voltage increase as the load is changed from one-fourth to one-half, and then to three-fourths and full load values. By testing each generator in this manner we can determine which of them has the greatest overcompounding effect, or produces the highest increase in voltage for the various increases in load.

If this compounding is found to be different on the various machines, it can be adjusted by means of the series field shunt, which will allow more or less of the total load current to flow through the series winding of the compound field.

When a number of machines of similar design are thus properly adjusted they should operate satisfactorily in parallel under all normal load changes.

In case the machines do not properly divide their loads and one is found to be taking more than its share of any load increases, this can be corrected by very slightly increasing the resistance of its series field circuit by adding a few feet of cable in the series field connection.

The series field windings may be connected to

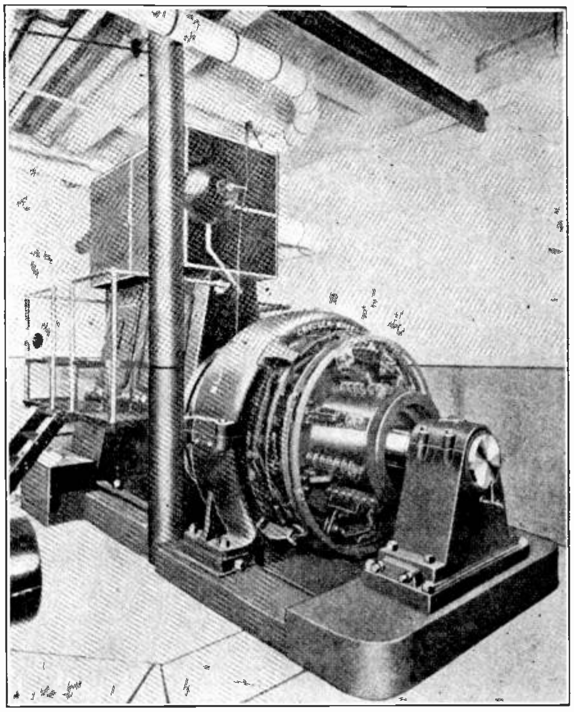


Fig. 42-A. Large D. C. generator driven by a vertical engine. If this machine is rated at 250 volts and 3000 amperes, what is its capacity and KW?

either the positive or negative brush leads of the armature; but, where compound generators are operated in parallel, **the series field lead of each machine must be connected to the same armature lead, either positive or negative, on all generators.**

42. EQUALIZER CONNECTIONS

When compound generators are operated in parallel, an **equalizer connection** should be used to equalize the proportion of currents through their series fields and to balance their compounding effects.

This equalizer connection, or bus, is attached to the end of the series field next to the armature. Its purpose is to connect the series fields of all generators directly in parallel by a short path of very low resistance, and to allow the load to divide properly between them. When this connection is properly made the current load will divide between the series fields of the several machines in proportion to their capacity.

The equalizer allows the total load current to divide through all series fields in inverse proportion to their resistance, independently of the load on the armature of the machine and of the armature resistance and voltage drop. This causes an increase of voltage on one machine to build up the voltage of the others at the same time, so that no one machine can take all the increased load.

The connecting cables or busses used for equalizer connections between compound generators should be of very low resistance and also of equal resistance. This also applies to the series field connections from the generators to the main buss, if the machines are of the same size.

If the machines are located at different distances from the switchboard, bus cables of slightly different size can be used, or an additional low resistance unit can be inserted in the lower resistance leads.

Whenever possible, leads of equal length should be used; and, in the case of cables, it is sometimes advisable to loop them or have several turns in the cable to make up the proper length. If these cables or busses were of unequal resistance on machines of the same size, there would be an unequal division of the load through the machines, and the machine having the lowest resistance would take more than its share of the load.

When machines of unequal size are to be paralleled, the resistance of the series field leads should be in proportion to the resistance of the series field windings.

Fig. 43 shows a wiring diagram for two compound generators to be operated in parallel. Note the series and shunt field windings, and also the series field shunts and shunt field rheostat. The equalizer connections are shown properly made at the point between the series field lead and the negative brush. From this point they are attached to the equalizer bus on the switchboard. The voltmeters are connected directly across the positive and negative leads of each generator, and the ammeters are connected across ammeter shunts which are in series with the positive leads of each machine. These shunts will be explained later.

The machine switches for connecting the generators to the bus bars are also shown in this diagram; but the circuit breakers, which would be connected in series with these switches, are not shown.

43. LOCATION OF EQUALIZER SWITCHES

On machines of small or medium sizes and up to about 1,000 ampere capacity, the equalizer switch is often the center pole of the three-pole switch, as shown in Fig. 43.

The two outside switch blades are in the positive and negative leads of the machine. For machines requiring larger switches, three separate single-pole switches may be used for greater ease of operation. In this case the center one is usually the equalizer switch.

It is quite common practice to mount all of these switches on the switchboard, although in some installations the equalizer switch is mounted on a pedestal near the generator. In this case, the equalizer cable or bus is not taken to the switchboard but is run directly between the two machines.

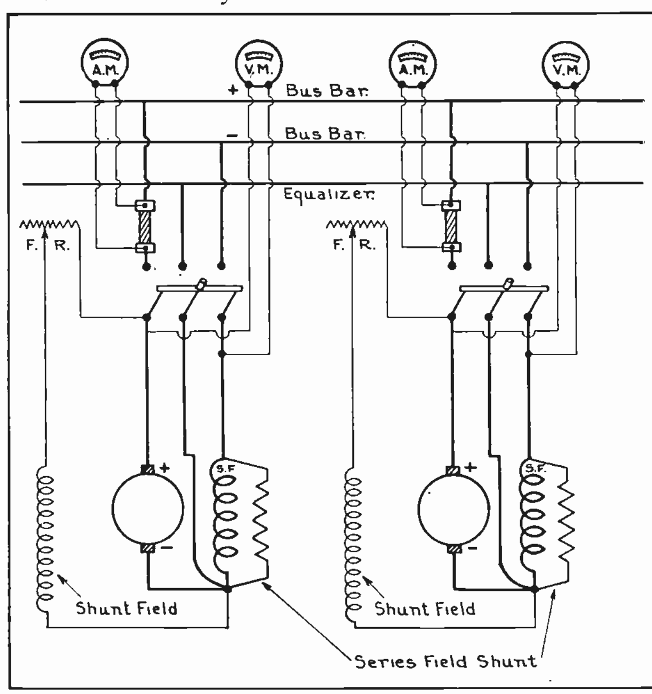


Fig. 43. This diagram shows the connections for two compound D. C. generators to be operated in parallel. Note carefully the connections of the equalizer leads, series and shunt fields and instruments.

Regardless of the location of the equalizer switches, **they should be closed at the same time or before the positive and negative machine switches are closed.**

Where three-pole switches are used, all of the poles are, of course, closed at the same time; but, if three single-pole switches are used, the equalizer should be closed first. If the positive and negative switches are closed one at a time, the switch on the same side of the armature from which the equalizer connection is taken should be closed second.

The series field should always be paralleled before or at the same instant that the generator armature is paralleled with the main bus, in order to insure equalization of the compounding effects and to allow the machine to take its proper share of the load at once.

44. INSTRUMENT CONNECTIONS WITH PARALLEL GENERATORS

Current instruments and devices—such as ammeters, overload coils on circuit breakers, current coils of wattmeters, etc.—should always be connected in the armature lead which doesn't contain the series field winding. This is shown by the ammeter shunts in Fig. 43, which are properly connected in the positive lead.

If these devices are connected in the lead which has the series field in it, the current indications will not be accurate, because current from this side of the machine can divide and flow through either the equalizer bus or the armature.

Ammeters and other current devices should indicate the amount of current through the armature of the machine. It is not necessary to measure the current through the series fields, since they are all in parallel with each other.

The voltage generated in the armature will determine the amount of current which is carried through it, and it is possible to control the armature voltage of any machine by the adjustment of the shunt field rheostat and thus vary the load carried by each generator.

Voltmeters should be connected, as shown in Fig. 43, at a point between the generator brushes and the main switch, so that the voltage readings can be obtained before this switch is closed. This is necessary because we must know the voltage of the generator before it is connected in parallel with the others.

45. STARTING, PARALLELING and ADJUSTING LOAD ON GENERATORS

In starting up a generator plant with several machines, the first generator can be started by the procedure previously described and connected to the bus as soon as its voltage is normal. The second generator should then be brought up to speed and its voltage then carefully checked and adjusted to be equal to that of the first machine. Then this second machine can be connected to the bus. The ammeters of both machines should then be read to see that they are dividing the load equally or in proportion to their sizes.

By adjusting the voltage of any generator with its field rheostat, it can be made to take its proper share of the load. After this adjustment is made, the same procedure can be followed on the remaining machines. If there are a number of branch circuits and switchboard panels feeding to the lines and load, the switches on these panels can be closed one at a time, applying the loads to the generators gradually.

To shut down any machine, adjust its shunt field rheostat to cut in resistance and weaken its field, lowering the voltage of that generator until its ammeter shows that it has dropped practically all of its load. The circuit breaker can then be opened and the machine shut down.

THREE-WIRE D. C. SYSTEMS

The Edison three-wire D. C. system is used chiefly where the generating equipment is to supply energy for both power and lighting. The advantages of this system are that it supplies 110 volts for lights and 220 volts for motors and also saves considerably in the amounts and cost of copper, by the use of the higher voltage and balancing of the lighting circuits.

Some of these features of 3-wire systems were also explained in Section 2, on Electrical Wiring.

One of the most simple and common methods of obtaining the two voltages on three-wire circuits is by connecting two 110-volt generators in series, as shown in Fig. 44.

We know that when generators are connected in series in this manner their voltages add together, so these two 110-volt machines will produce 220 volts between the outside or positive and negative wires. The third, or neutral, wire is connected to the point between the two generators where the positive of one and negative of the other are connected together. The voltage between the neutral wire and either outside wire will be 110 volts, or the voltage of one machine.

Generators for this purpose may be either shunt or compound, but the compound machines are more generally used. They can be driven by separate prime movers or both driven by the same prime mover if desired; and the drive may be either by belt or direct coupling.

In general the operation of a three-wire system is practically the same as for a two-wire machine. The voltage of each generator may be adjusted by means of the shunt field rheostat.

As these machines are operated in series instead of parallel, it is not necessary to have their voltage exactly even; but they should be kept properly adjusted in order to maintain balanced voltages on the two sides of the three-wire system.

There is no division of the current load between these generators—as in the case of parallel machines—as the main current flows through both machines in series. When the voltage of both machines is properly adjusted, they can be connected to the switchboard busses. The ammeters should then be observed to note the current in each wire.

46. DIRECTION AND AMOUNT OF CURRENT IN THE NEUTRAL WIRE

The ammeter in the neutral wire is of the double-reading type, with the zero mark in the center of the scale, and it will read the amount of current flowing in either direction.

When the load on a three-wire system is perfectly balanced, the neutral wire will carry no current and the set operates on 220 volts. In this case the two outside ammeters will read the same and the center ammeter will read zero. When there is an unequal amount of load in watts on each side of the system it is said to be unbalanced, and the neutral wire will carry current equal to the difference between the current required by the load on one side and that on the other.

This current may, therefore, flow in either direction, according to which side of the system has the heaviest load. Referring to Fig. 44—if the greater load were on the lower side, the extra current required would be furnished by the lower generator; and the current in the neutral wire would be flowing to the right, or away from the generators. If the heavier load were placed on the upper side of the system, the extra current would be supplied by the upper machine, flowing out on its positive wire and back to the line on the neutral wire.

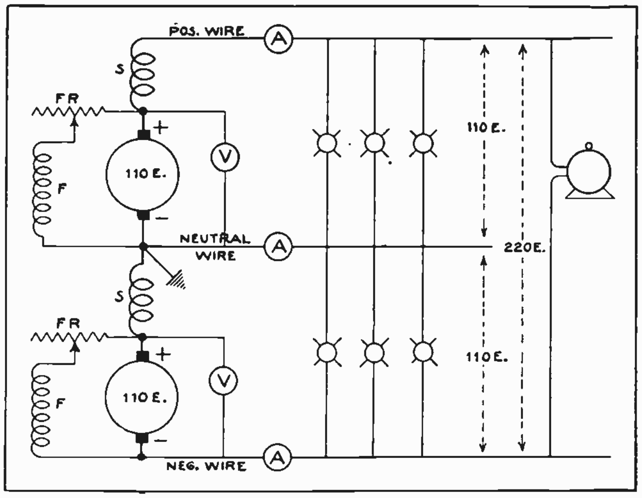


Fig. 44. This sketch shows two D. C. generators connected in series for providing three-wire, 110 and 220 volt service.

47. BALANCED SYSTEM MORE ECONOMICAL

For efficient operation, the amount of unbalance should not exceed 10% of the total load. In many cases, however, it is allowed to exceed 15% or more. If the load could always be kept perfectly balanced, no neutral wire would be required as all of the load devices would be operated two in series on 220 volts.

Without the neutral wire, if one or more of the lamps or devices should be disconnected, the remaining ones on the other side of the system would operate at more than normal voltage. This was thoroughly explained under the heading, "Three-Wire Systems", in Section Two of Electrical Construction and Wiring.

In most systems it is practically impossible to keep the load balanced at all times, and, therefore, the neutral wire is necessary to carry the unbalanced load and keep the voltages equal on both sides of the system. It is very seldom, however, that the neutral wire will have to carry as much current as the outside wires. Therefore, it may be made smaller than the positive and negative wires.

Quite often the neutral wire is made one-half the size of either of the outer wires, unless local rulings require it to be of the same size. If the neutral wire is made one-half the size of the outer ones, a three-wire system of this type will require only 31.3% of the copper required for the same load on a two-wire, 110-volt system.

The neutral wire is generally grounded, as shown in Fig. 44.

48. THREE-WIRE GENERATORS

In some cases a special three-wire generator is used, instead of the two machines in series, to produce a three-wire D. C. system. An early type of three-wire generator, and one which is still used for certain installations, consists of a 220-volt armature equipped with both a commutator and slip rings.

The armature coil connections are made to the commutator in the usual manner, and 220 volts is obtained from the brushes on the commutator. In addition to the leads from each coil to the commutator bars, other leads are taken from points spaced 180° apart around the winding and are connected to a pair of slip rings mounted on the shaft near the end of the commutator. This supplies single-phase alternating current at 220 volts to the slip rings.

From the brushes on these slip rings two leads are taken to opposite ends of a choke coil, which consists of a number of turns of heavy wire wound on an iron core similar to a transformer core. This connection is shown in Fig. 45.

A tap is made at the exact center of this choke coil for the third or neutral wire. In some cases a choke coil is mounted on the armature shaft and rotated with it; but in most cases this coil is stationary and outside of the machine, having its connections made through the slip rings and brushes. These coils are often referred to as three-wire transformers or compensators.

49. PRINCIPLE OF THE BALANCE COIL

The neutral wire, being connected to the center of the coil, is always at a voltage about one-half that between the positive and negative brushes. Therefore, if 220 volts are obtained between these brushes, 110 volts are obtained between either the positive and negative wire and the neutral.

When the load on a three-wire generator of this type is perfectly balanced, no current flows in the neutral wire and all of the load current is supplied from the commutator by the positive and negative D. C. brushes. There is, however, a small amount of alternating current flowing through the **choke or balance** coil at all times, as there is an alternating voltage applied to it from the slip rings as long as the machine is operating. This current will be very small, as a choke coil of this type offers a very high impedance or opposition to the flow of alternating current.

This impedance, or opposition, is composed of the ohmic resistance of the conductors in the coil, and also of the counter-voltage generated by self-induction whenever alternating current is passed through such turns of wire wound on an iron core.

Direct current, however, can flow through a coil of this type with only the opposition of the copper resistance, as the flux of direct current is not constantly expanding and contracting like that of alternating current, and so doesn't induce the high counter-voltage of self-induction.

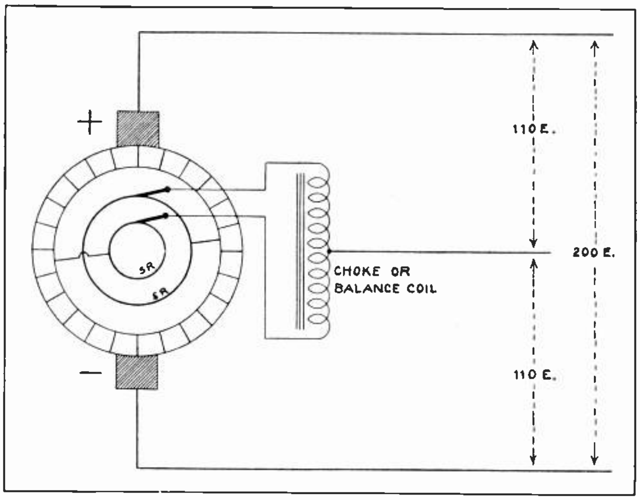


Fig. 45. The above diagram shows the commutator, slip rings, and balance coil of a three-wire D. C. generator.

50. UNBALANCED LOAD ON THREE-WIRE GENERATORS

When a system such as that shown in Fig. 45 is unbalanced and has, we will say, a heavier load between the positive wire and neutral, the unbalanced current flowing in the neutral wire will return to the center tap of the choke coil. From this point it will flow first in one direction and then in the other, as the alternating current reverses in direction through the coil. Thus it returns to the armature winding, through first one slip ring and then the other.

If the lower side of the circuit is loaded the heaviest the unbalanced current will flow out through the choke coil in the same manner, passing first through one half and then the other, to reach the neutral wire.

The choke coil must, of course, be wound with wire large enough to carry the maximum unbalanced current that the neutral wire is expected to carry. It must also have a sufficient number of turns to limit the flow of alternating current from the slip rings to a very low value, in order to prevent a large waste of current through this coil.

Three-wire generators of this type can stand considerable unbalanced load without much effect on the voltage regulation. They are very compact and economical and are used to some extent in small isolated D. C. plants, where the circuits carry a load of 110-volt lamps and equipment, and also 220-volt motors.

Fig. 46 shows a three-wire generator on which the slip rings can be seen mounted close to the end of the commutator.

51. THREE-WIRE MOTOR GENERATORS OR BALANCER SETS

Three-wire circuits may also be obtained by means of a 220-volt D. C. generator in combination with a motor-generator or balancer set. These balancer sets consist of two 110-volt machines mounted on the same bed plate and directly connected together by their shafts. See Fig. 48. The armatures of both machines are connected in series with each other, and across the positive and negative leads of the 220-volt generator, as shown in Fig. 47.

This allows 110 volts to be applied to each armature and operates both machines as motors when the load is perfectly balanced. Either machine can, however, be operated either as a motor or as a generator, if the load on the system becomes unbalanced.

If one side of the system has a heavier load connected to it, the machine on this side automatically starts to operate as a generator and is driven by the machine on the other side, which then operates as a motor. This condition will immediately reverse if the greater load is placed on the opposite side of the system. A balancer set of this type will, therefore, supply the unbalanced current in either direction, and will maintain 110 volts between the neutral and either outside wire.

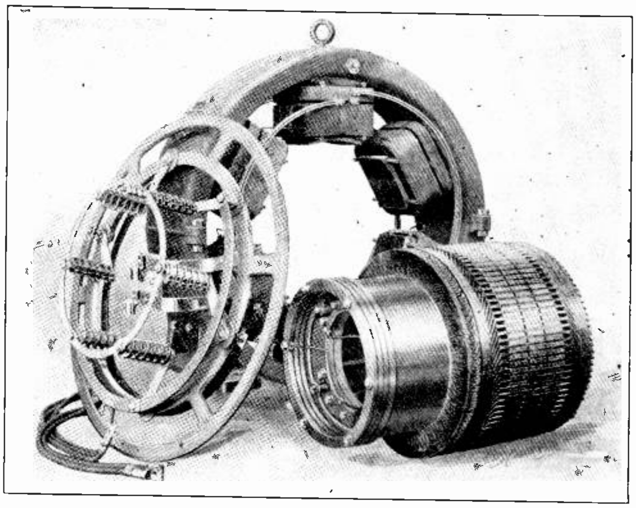


Fig 45-B. This view shows a three-wire generator disassembled. You will note the slip rings mounted on the end of the commutator.

Where these machines are larger than one or two kilowatts, a starting rheostat should be used to limit the flow of current through their armatures until the machines attain full speed. After they reach full speed, they generate sufficient counter-voltage to limit the current flow through their armatures while operating as motors.

The neutral wire is connected between the armatures of the motor generator set where their positive and negative leads connect together.

52. EFFECTS OF SHUNT AND SERIES FIELDS OF BALANCER GENERATORS

Either shunt or compound machines may be used for these equalizers, but compound machines are

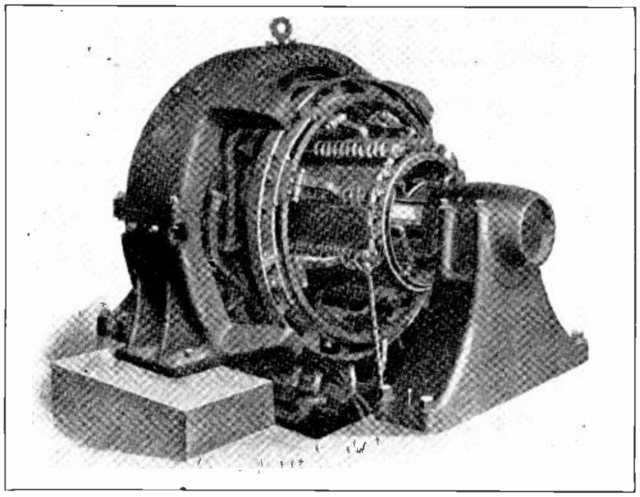


Fig. 46. Assembled three-wire generator. Slip rings can be seen at the right-hand end of the commutator. If this machine is rated at 500 KW, what should the maximum load in amperes be on both of the 110 volt circuits it supplies?

used more extensively. The number of turns in the series field coils must be carefully selected to provide the proper compounding effects. Generally the number of turns is very small, so that the voltage rise due to compounding will not be very great.

If this series field produces too great a voltage rise on either machine, that machine will be apt to take more than the unbalanced part of the load. The machines shown in Fig. 47 are of the compound type and have their series fields connected in series with the armatures and the positive and negative line wires.

The shunt fields are connected in parallel with their armatures and are both in series with a field rheostat, which can be used to increase the strength of the field of one machine and decrease that of the other at the same time.

The series fields are connected so that they increase the field strength when either machine is operating as a generator, but tend to decrease or oppose the flux of the shunt field on either machine when it operates as a motor. This is caused by the reversal of the direction of current through the series field and armatures as the unbalanced load is shifted from one side of the system to the other. Current through the shunt fields, however, continues to flow in the same direction at all times, because they are connected across the positive and negative leads from the main generator.

If the compounding effect of the balancer machines tends to strengthen the field of either one operating as a generator, the voltage of that machine will rise slightly; while the compound effect on the machine operating as a motor weakens its field and tends to make it speed up.

As long as the load on the system is perfectly balanced, both machines operate as differential motors without any mechanical load. The current through their armatures at such times is very small, being only sufficient to keep the armatures turning against the bearing and friction losses and to supply the small electric losses in the machines.

53. BALANCING OF UNEQUAL LOADS

When a system is unbalanced, the neutral current divides between the two armatures, driving the one on the lightly loaded side as a motor and passing through the other as a generator. In Fig. 47 the upper side of the system has the heaviest load, and the lower side has the highest resistance. This will cause the excess current from the greater load to flow back through the neutral wire and through the series of the lower machine, in a direction opposing its shunt field. This weakens the field flux and causes this machine to speed up and tend to act as a motor to drive the upper machine as a generator.

As the voltage of the generator unit rises slightly with the increased speed, it causes part of the unbalanced load to flow through it, and its series field, in a direction aiding the flux of the shunt field.

This increases its voltage still more, which enables it to take its proper share of the unbalanced current and to compensate for the voltage drop on the heavily loaded side of the system.

If the heaviest load is placed on the other side of the system, the current through the series fields of both machines will reverse, and cause the one which was operating as a generator to speed up and operate as a motor.

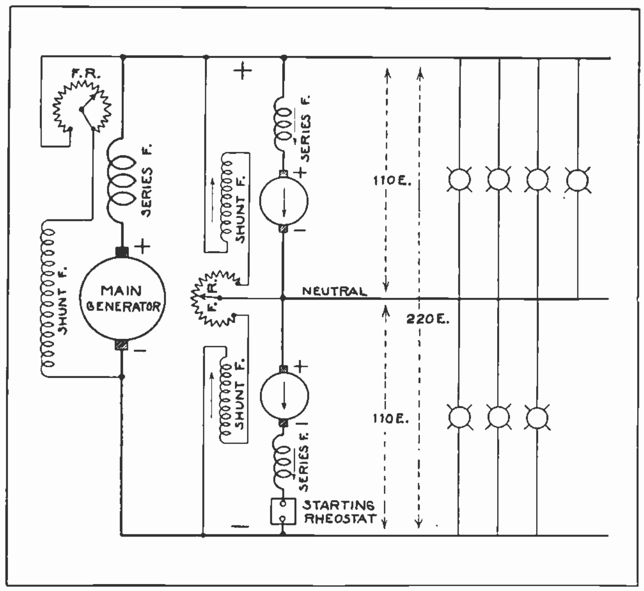


Fig. 47. This diagram shows the connections for the main generator and two balancer machines of a three-wire system.

The motor armature must take enough more than one-half of the neutral current to supply the losses of both armatures.

Referring again to Fig. 47, we find that the connections of the field rheostat, F. R., are such that when the handle or sliding contact is moved upward it will cut resistance out of the shunt field of the upper machine and add resistance in series with the shunt of the lower machine. This would produce the desired effects when the upper machine is operating as a generator and the lower one as a motor.

As this change of resistance increases the field strength voltage of the generator, it weakens the field strength and increases the speed of the motor.

The shunt fields can be controlled separately, if desired, by connecting a separate rheostat in series with each field. In Fig. 44 the shunt fields of each machine are connected in parallel with their own armatures. By changing these connections so that the shunt field of each machine is connected across the armature of the other mahine, the machine which is operating as a generator will increase the current flow through the motor field and improve the torque of the motor armature.

Fig. 48 shows a motor-generator balancer set of the type just described.

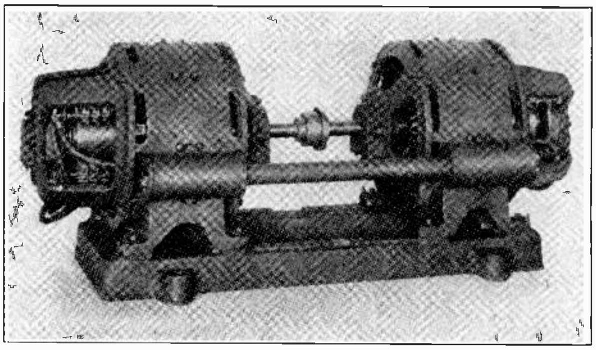


Fig. 48. Photo of a motor-generator balancer set used for three-wire system machines of this type are used considerably, where the unbalanced load is small compared to the total load on the main generator.

COMMUTATION AND INTERPOLES

The term "commutation" applies to the process of reversing the connections of the coils to the brushes, as the coils pass from one pole to another in rotation.

The function of the commutator, as we already know, is to constantly deliver to the brushes voltage in one direction only, and thereby rectify or change the alternating current generated in the winding to direct current for the line.

We have also learned that commutation for the various coils, or the contact of their bars with the brushes, should take place when the coils are in the neutral plane between adjacent poles; at which point there is practically no voltage generated in them.

The reason for having commutation take place while the coils are in the neutral plane is to prevent short-circuiting them while they have a high voltage generated in them. This would cause severe sparking, as will be more fully explained later.

54. PROCESS OF COMMUTATION

The process of commutation, or shifting of coils in and out of contact with the brushes, is illustrated in Fig. 49. Here we have a sketch of a simple ring-type armature with the ends of the coils shown connected to adjacent commutator bars. This winding is not the kind used on modern power generators, but it illustrates the principles of commutation very well, and is very easily traced.

We will assume that the armature in this figure is rotating clockwise. All of the coils which are in front of the north and south poles will be generating voltage, which we will assume is in the direction shown by the arrows inside the coils.

As the coils are all connected in series through their connections to the commutator bars, the voltage of all of the coils on each side of the armature will add together. The voltages from both halves of the winding cause current to flow to the positive brush, out through the line and load, and back in at the negative brush where it again divides through both sides of the winding.

Now let us follow the movement of one coil through positions A, B, and C; and see what action takes place in the coil during commutation.

We will first consider the coil in position A, which is approaching the positive brush. This coil is carrying the full current of the left half of the winding, as this current is still flowing through it to commutator bar 1 and to the positive brush. The coil at "A" also has a voltage generated in it, because it is still under the edge of the north field-pole.

An instant later when the coil has moved into position B, it will be short-circuited by the brush coming in contact with bars 1 and 2.

55. SELF INDUCTION IN COILS SHORTED BY BRUSHES

As soon as this coil is shorted by the brush, the armature current stops flowing through it, and flows directly through the commutator bar to the brush. When this current stops flowing through the coil, the flux around the coil collapses and cuts across the turns of its winding, inducing a voltage in this shorted coil. This is called **voltage of self-induction,** and it sets up a considerable current flow in the shorted coil, as its resistance is so low. Note that **the voltage of self-induction always tends to maintain current in an armature coil in the direction it was last flowing when generated from the field pole.**

As long as the coil remains shorted, the current set up by self-induction flows around through the coil, bars, and brush. But as the coil moves far enough so bar 2 breaks contact with the brush, this interrupts the self-induced current and causes an arc. Arcing or sparking will tend to burn and pit the commutator, and is very detrimental to the commutator surface and brushes. Methods of preventing arcing will be explained later.

As the coil which we are considering moves on into position C, its short circuit has been removed and it is now cutting flux under a north pole. This will generate a voltage in the opposite direction to what it formerly had, and it still feeds its current back to the positive brush through bar 2.

So we find that, by shifting the contact from one end of the coils to the other as they pass from pole to pole and have their voltages reversed, the same brush always remains positive.

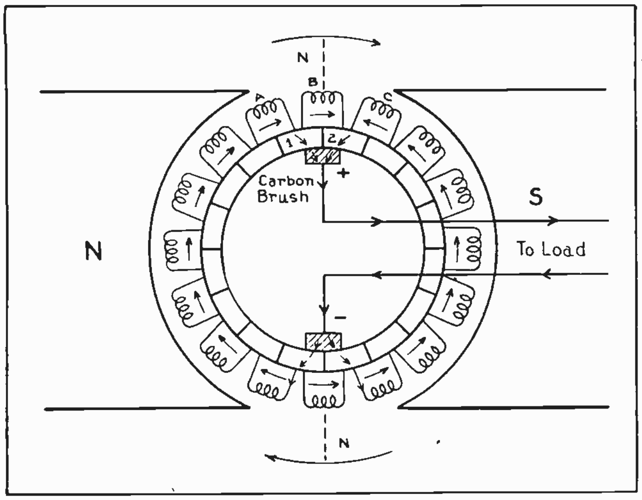


Fig. 49. This diagram illustrates the principles of commutation in a generator. Examine each part of it very carefully while reading the explanation given on these pages.

56. IMPORTANCE OF PROPER BRUSH SETTING FOR NEUTRAL PLANE

The time allowed for commutation is extremely short, because when a generator armature is turning at high speed, the bars attached to any coil are in contact with a brush for only a very small fraction of a second.

The reversal of the coil leads to the brushes must take place very rapidly as the coils are revolved at high speed from one pole to the next. On an ordinary four-pole generator each coil must pass through the process of commutation several thousand times per minute. Therefore, it is very important that commutation be accomplished without sparking, if we are to preserve a smooth surface on the commutator and prevent rapid wear of the brushes.

Brushes are made in different widths according to the type of winding used in the machine; but, regardless of how narrow the brushes may be, there will always be a short period during which adjacent commutator bars will be shorted together by the brushes as they pass under them.

We have found that, in order to avoid severe sparking during commutation, the coils must be shorted only while they are in the neutral plane, when the coil itself is not generating voltage from the flux of the field poles. Therefore, the brushes must be accurately set so they will short circuit the coils only while they are in this neutral plane.

57. SHIFTING BRUSHES WITH VARYING LOAD ON MACHINES WITHOUT INTERPOLES

The neutral plane tends to shift as the load on a generator is increased or decreased. This is due to the fact that increased load increases the current through the armature winding and the additional armature flux will cause greater distortion of the field flux. **The greater the load, the further the neutral plane will move in the direction of armature rotation.**

If the brushes are shifted to follow the movement of this neutral plane with increased load, commutation can still be accomplished without severe sparking. For this reason, the brushes are usually mounted on a rocker arm which allows them to be shifted or rotated a short distance in either direction around the commutator.

In addition to the sparking which is caused by shorting coils which are not in the neutral plane, the other principal cause of sparking is the self-induced current which is set up in the coils by the collapse of their own flux when the armature current through them is interrupted.

We have previously stated that this self-induction will set up a considerable flow of current in the shorted coils. Then, when the coil moves on and one of its bars moves out from under the brush and thus opens the short circuit, this current forms an arc as it is interrupted.

Sparking from this cause can be prevented to a large extent by generating in the coil a voltage which is equal and opposite to that of self-induction.

Shifting the brushes also helps to accomplish this, by allowing commutation to take place as the coil is actually approaching the next field pole.

This is illustrated in Fig. 50. In this figure you will note that the brushes have been shifted so that they do not short circuit the coils until they are actually entering the flux of the next pole beyond the normal neutral plane.

The voltage of self-induction always tends to set up current in the same direction as the current induced by the field pole which the coil is just leaving. If, at the time the short circuit on the coil is broken, the coil is entering the flux of the next pole, this flux will induce in the coil a voltage in the opposite direction to that of self-induction. This will tend to neutralize the voltage and currents of self-induction and enable the short circuit to be broken when there is practically no voltage or current in the shorted coil.

Keep in mind that this is the required condition for most satisfactory commutation.

If the load on generators doesn't change often

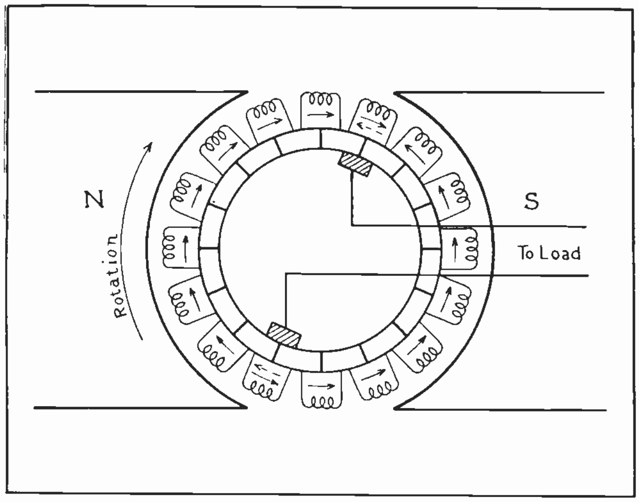


Fig. 50. **This sketch shows the method of shifting the brushes to short circuit coils in a position where they will be generating the voltage to neutralize that of self-induction.**

or suddenly, manual shifting of the brushes with each change of load and new position of the neutral plane, may be all that is required to prevent sparking; but when the load changes are frequent and considerable, it would be very difficult to maintain this adjustment by hand.

Where the manual method is used to maintain proper commutation, it is common practice to adjust the brushes to a position where they will spark the least for the average load. Then, even though a certain amount of sparking results when the load rises above or falls below this value, the brushes are not changed unless the sparking becomes too severe.

Fig. 51 shows a D. C. generator without the shaft or bearing post. The brushes of this machine are all attached to the ring framework as shown, and this entire assembly can be rotated to shift the brushes, by means of the hand wheel at the left.

Referring again to Fig. 50, the solid arrows show the direction of the voltage of self-induction, and the dotted arrows show the direction of the voltage which is induced by the flux of the field pole which the coil is approaching. These two voltages, being in opposite directions, tend to neutralize each other, as has previously been explained.

58. USE OF COMMUTATING POLES TO PREVENT SPARKING

On the more modern D.C. machines **commutating poles, or interpoles,** are employed to hold the neutral plane in its normal position between the main poles, and to neutralize the effects of self-induction in the shorted coils. These interpoles are smaller field poles which are mounted in between the main poles of the machine, as shown in Fig. 52.

The interpoles are wound and connected so they will set up flux of proper polarity, to generate voltage in the opposite direction to that of self-induction, as the armature coils pass under them. Fig. 53 shows a sketch of a simple generator with interpoles, or commutating poles, placed between the main field poles.

We will assume that this armature is rotated in a clockwise direction, and that its armature conductors have generated in them voltage which tends to send current in through the conductors on the left side, and out through those on the right side of the winding. Recalling that the voltage of self-induction tends to maintain current in the same direction in the conductor as it was under the last field pole, we find that this voltage is generated "in" at the top conductor in the neutral plane and "out" at the lower one.

59. POLARITY OF INTERPOLES FOR A GENERATOR

If you will check the polarity of the interpoles, you will find that their flux would be in a direction to induce voltages opposite to those of self-induction in each of these two conductors. The direction of these voltages is shown by the symbols placed just outside of the conductor circles. So we find that, if these commutating poles are made to set up flux of the right polarity and in the right amount, they can be caused to neutralize the effects of self-induction and distortion of the neutral plane almost entirely.

These poles are called "commutating poles" because their principal purpose is to improve commutation and reduce sparking at the commutator and brushes.

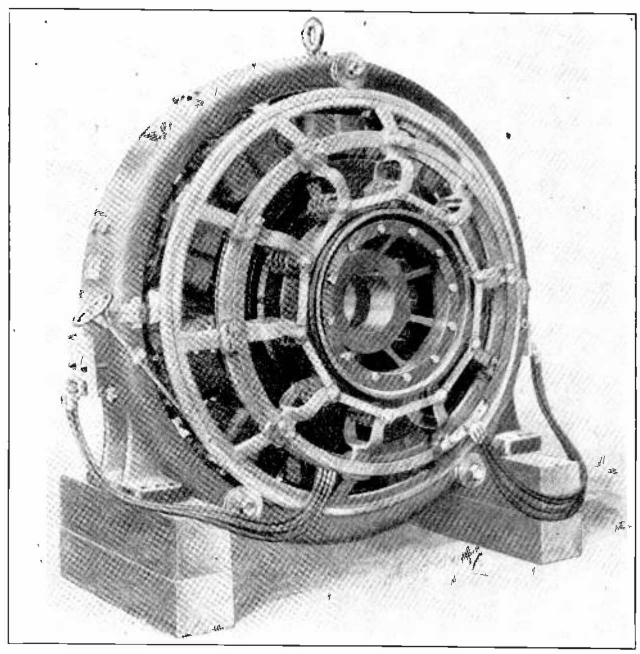


Fig. 51. **This end view of a generator with the pedestals, bearing, and shaft removed shows very clearly the brush ring mounted in grooved rollers on the side of the field frame. The hand-wheel at the left can be used for rotating this ring to shift the brushes to the proper neutral plane.**

In order to produce the desired results **the interpoles of a generator must be of the same polarity as the adjacent main pole in the direction of rotation.**

60. STRENGTH OF COMMUTATING FIELD VARIES WITH LOAD

In order that these commutating poles may produce fields of the proper strength for the varying loads on the generator armature, their windings are connected in series with the armature, so that their strength will at all times be proportional to the load current. In this manner, the strength and neutralizing effect of the interpoles increases as the load increases, and thereby tends to counteract the effect of increased load on field distortion and self-induction.

In this manner, interpoles can be made to maintain sparkless commutation at all loads and thus make unnecessary the shifting of the brushes for varying loads.

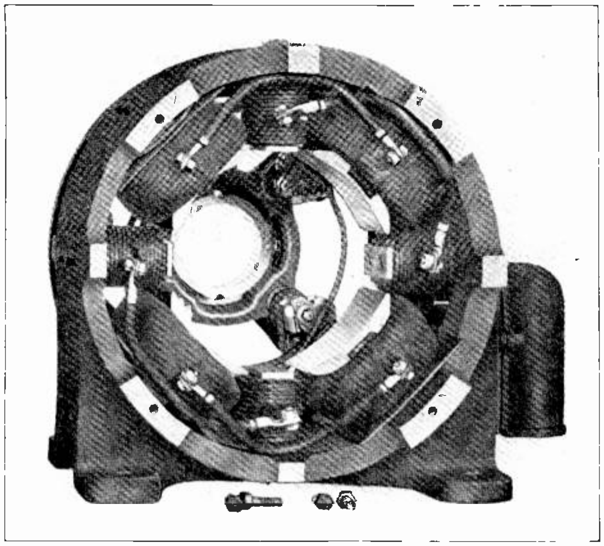


Fig. 52. This photo shows a four-pole, D. C. generator with commutating poles. These commutating poles or interpoles are the smaller ones shown between the main field poles.

Referring again to Fig. 52, you will note that the windings on the interpoles consist of a few turns of very heavy cable, so that they will be able to carry the armature current of the machine. The strength of the interpoles can be varied by the use of an **interpole shunt,** which is connected in parallel with the commutating field to shunt part of the armature current around these coils. The connections of this shunt are shown in Fig. 54-A. The interpole shunt is usually made of low resistance materials, such as bronze or copper, so it will carry the current readily without undue heating.

This method of weakening the strength of the commutating field is quite commonly used on the larger machines. The terminals of the commutating field are usually connected directly to the brushes, to eliminate confusion when making external connections to the machine.

61. ADJUSTMENT OF BRUSHES ON INTERPOLE MACHINES

On machines of small and medium sizes, the end plate or bracket on the generator is sometimes slotted, as shown in Fig. 54-B, to allow the brushes to be rotated or shifted within a very limited range. With such machines, the brush-holder studs are

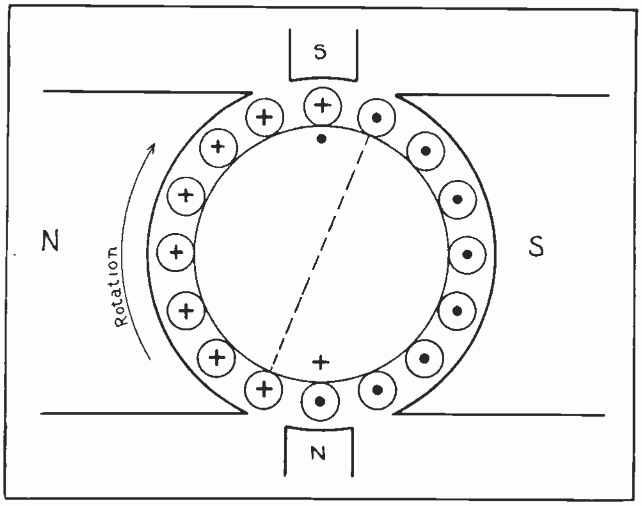


Fig. 53. This sketch illustrates the manner in which interpoles generate voltage opposite to that of self-induction in the conductors which are shorted by the brushes.

mounted rigidly in the bracket but are, of course, insulated from the metal with fibre sleeves and washers.

When the brushes are to be rotated the bolts which hold the end plate to the field frame are loosened slightly and the entire end plate is shifted. This allows the armature coils to be commutated at a point where the effects of the interpole are just great enough to neutralize or balance self-induction.

Before removing the end plate to make repairs on a machine of this type, it is well to mark its position, so that you can be sure to get it replaced in the correct position. This can be done by making one or two small marks in line with each other on both the field frame and the end plate. The marks can be made with a file or prick punch.

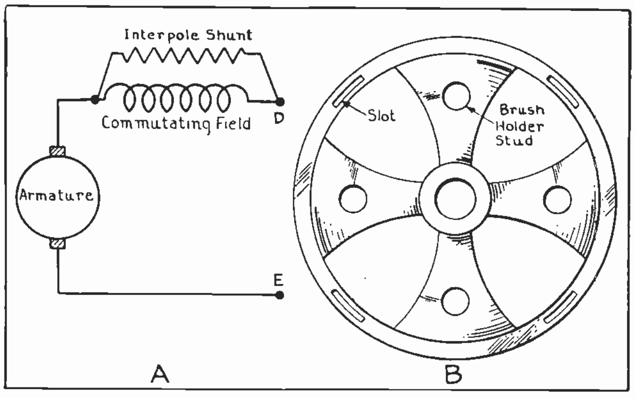


Fig. 54. At "A" is shown the connection of an interpole shunt for varying the strength of the commutating field. "B" shows an end bracket with slots to allow it to be rotated slightly to shift the brushes. The brush holders on this machine would be mounted on this end bracket.

62. ADJUSTING INTERPOLES BY CHANGING THE AIR GAP

The strength of interpoles can also be varied by placing iron shims or thin strips between the interpole and the field frame of the machine, as shown in Fig. 55. It is possible in this manner to vary the width of the air gap between the face of the interpoles and the armature core.

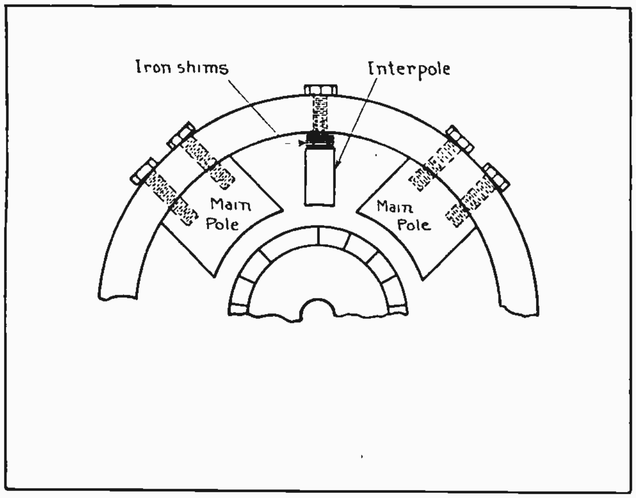


Fig. 55. Thin iron shims can be used under an interpole to vary its strength by changing the air gap between the pole and the armature.

Decreasing the air gap reduces the magnetic reluctance of the interpole field path, thereby strengthening its flux and increasing its effect on commutation. This method can be used on machines of any size and when no other visible means of varying the interpole strength is provided, shims are probably used.

On some machines, the number of interpoles may only be one-half the number of main field poles; in which case they will be placed in every other neutral plane and will all be of the same polarity. By making these interpoles of twice the strength as would be used when a machine has one for each main pole, we can still effectively neutralize the self-induction in the coils. This is true because, with a modern drum-wound armature, when one side of any coil is in one neutral plane the other side will be in the adjacent neutral plane.

For this reason, if interpoles are placed in every other neutral plane, one side of any coil will always be under the interpole while this coil is undergoing commutation. This is illustrated by the sketch in Fig. 56, which shows a four-pole generator with only two interpoles.

As both sides of any coil are in series, the double strength of the interpole over one side will neutralize the effects of self-induction in the entire coil. This type of construction reduces the cost of the generator considerably and is often used on machines ranging up to six-pole size.

63. COMMUTATION ON MOTORS

The problem of obtaining sparkless commutation on D. C. motors is practically the same as with D.C. generators.

Motors as well as generators must have the connections from the brushes to the coils reversed as the coils pass from one pole to another of opposite polarity. This is necessary to keep the current from the line flowing in the right direction in all coils in order to produce torque in the same direction under all field poles.

During commutation, the coils of a motor armature are momentarily short circuited by the brushes, the same as with a generator.

This shorting and commutation should take place while the coils are in the neutral plane between the field poles, where they are doing the least work or producing the least torque.

We also know that the coils of any motor armature have a high counter-voltage generated in them as they rotate under the field poles. This counter-voltage will be at its lowest value while the coils are passing through the neutral planes; which is another reason for having commutation take place at this point in a motor.

64. POSITION OF NEUTRAL PLANE IN MOTORS

The neutral plane of a D.C. motor will also shift with load variations and changes in armature current, but this shift will be in the opposite direction to what it is in a generator. This is due to the fact that the rotation of a motor will be opposite to that of a generator if the current direction is the same in the motor armature as in the generator armature.

Motor coils also have counter-voltage of self-induction produced in them when they are shorted by the brushes. In a motor, the direction of this self-induced voltage will be opposite to that in a generator, as the motor armature currents are in the opposite direction to those in a generator armature of the same direction of rotation.

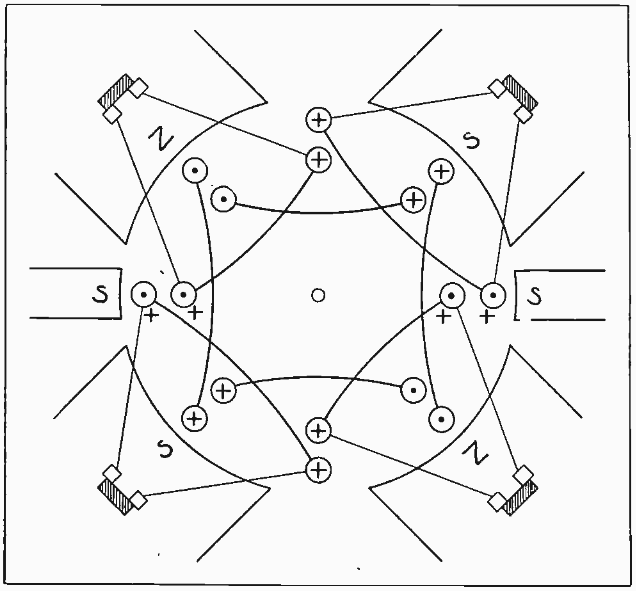


Fig. 56. This simple sketch illustrates the manner in which two interpoles can be used to neutralize self-induction in the coils of a four-pole machine.

We can, therefore, improve commutation on a motor by shifting the brushes in the opposite direction to that used for a generator. **Motor brushes should be shifted against the direction of rotation, when the load is increased.**

Fig. 57 is a sketch of the armature conductors and field poles of a simple D.C. motor, showing the position of the neutral plane with respect to the direction of rotation.

The heavy symbols in the six armature conductors on each side show the direction of the applied current from the line, which is flowing "in" on the conductors at the right and "out" on those on the left side. The lighter symbols in the single conductors at the top and bottom show the direction of the currents set up in this coil by self-induction when the coil is shorted. The symbols shown outside of the conductor circles indicate the direction of the counter E.M.F. produced in the motor winding. This counter-voltage always opposes the direction of the applied line voltage.

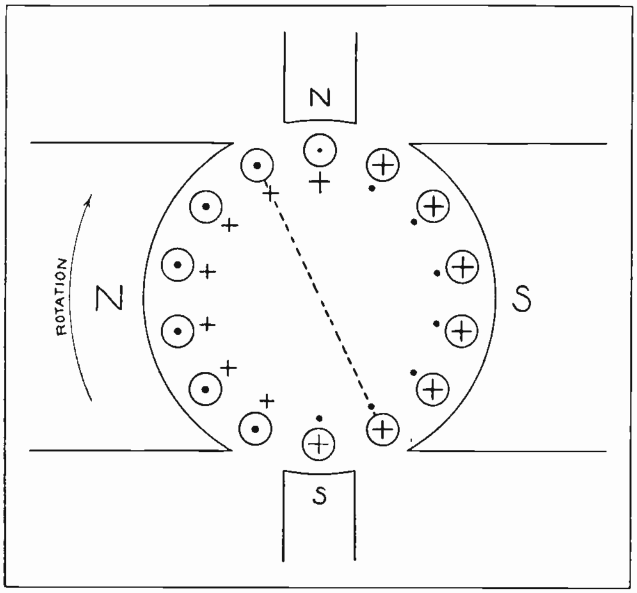


Fig. 57. This sketch shows the position of the neutral plane with respect to rotation in a motor. Compare this with Fig. 53 for a generator.

65. POLARITY OF INTERPOLES FOR MOTORS

Interpoles or commutating fields can also be used on motors to improve commutation at all loads and to eliminate the necessity of frequent shifting of the brushes.

On a motor, these interpoles are connected in series with its armature, the same as those of a generator are, but **the polarity of motor interpoles must be the same as that of the adjacent main poles in the opposite direction to rotation.** This is because the self-induced voltages in the coils shorted by the brushes in a motor are opposite to those in a generator with the same direction of rotation.

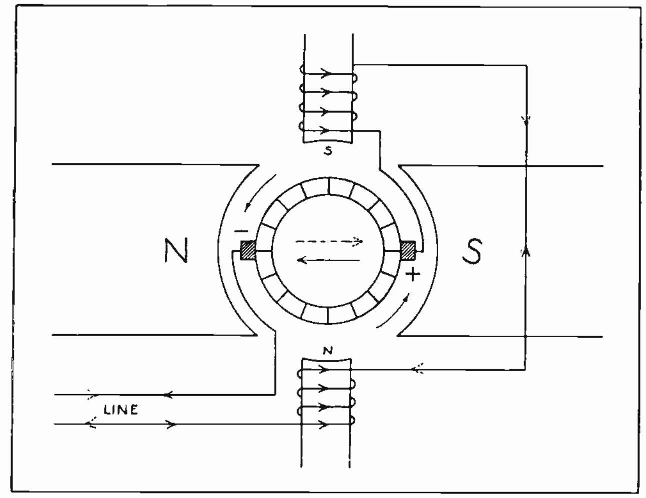


Fig. 58. This diagram shows the connections of the interpoles for a two-pole generator or motor.

Fig. 58 shows the connections of the interpoles for a two-pole D.C. motor. You will note that one armature lead is connected directly to the negative brush, while the other lead connects first to the commutating field and then, through these poles, to the positive brush.

If this connection is properly made when the machine is assembled, it is not necessary to make any change in the connections of the commutating field when the motor is reversed. Either the armature current or field poles must be reversed to reverse the rotation, so that the relation of the commutating poles will still be correct.

This connection can be the same whether the machine is operated as a motor or generator, because a generator rotated in the same direction as a motor will generate current in the opposite direction through the armature. This is shown by the dotted arrows in Fig. 58, while the solid arrows show the direction of motor current.

As the commutating poles are in series with the armature, this reversed current will also reverse the polarity of the commutating field, and maintain the proper polarity for generator operation.

These principles of commutation and interpoles should be kept well in mind, as an efficient maintenance electrician or power plant operator will never allow unnecessary sparking to damage the brushes and commutator of machines of which he has charge.

COYNE
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ESTABLISHED 1899

DIRECT CURRENT POWER AND MACHINES

Section Two

Switchboards and Switchgear
Knife Switches, Circuit Breakers, Relays, Busses
Switchboard Layout and Wiring
D. C. Meters
Voltmeters, Ammeters, Wattmeters
Kilo-watt Hour Meters, Operation, Reading and Testing
Recording Instruments, Demand Meters
Wheatstone Bridge
Megger.

D. C. SWITCHBOARDS

In power plants, substations, and industrial plants where large amounts of electric power are generated or used, it is necessary to have some central point at which to control and measure this power. For this purpose switchboards are used.

The function of the switchboard is to provide a convenient mounting for the knife switches, circuit breakers, rheostats, and meters which are used to control and measure the current. The equipment located on the switchboard is generally called **switchgear.**

66. TYPES OF SWITCHBOARDS

Switchboards are of two common types, known as **panel boards** and **bench boards.** The latter are also called **Desk-type** boards.

Panel-type boards consist of vertical panels of the proper height and width, on the face of which the switchgear is mounted. On the rear of the board are located the bus bars and wires which connect the switches, circuit breakers, and meters to the various power circuits which they control or measure the energy of. Fig. 59 shows a panel-type switchboard for a D. C. power plant. Examine it carefully and note its construction and the arrangement of the equipment mounted on it.

Bench-type switchboards have the lower section built like a bench with a sloping top, and above the rear edge of the bench section is a vertical panel which contains the instruments.

The sketch in Fig. 60 shows an end view of a bench-type switchboard with the panels mounted on a pipework frame. Boards of this type are used mostly for remote-control switchboards, where the switches and circuit breakers are operated by electro-magnets and solenoids, which are controlled by small push-button or knife switches on the bench portion of the board.

Another type of switchboard which is frequently used in industrial power plants is known as the **truck type.** These boards are built in separate sections, which can be drawn out on rollers for convenient repairs and adjustment to switchgear. Fig. 61 shows a section of a truck-type board, removed from the main board, and showing the oil switch and bus bars which are mounted in the frame behind the front panel.

Bench-type and truck-type switchboards will be more fully explained in a later section on A. C. switchboards.

67. SWITCHBOARD PANEL MATERIALS

Switchboard panels are sometimes made of slate or marble, as these materials are good insulators and have good mechanical strength as supports for the switchgear.

Slate is cheaper than marble and is easier to drill and cut for mounting on the frames and for mounting the switchgear. Slate is not quite as good an insulator, however, and is usually not used for voltages over 500 or 750.

Marble is a better insulator and can be used on voltages up to 1100. Marble presents an excellent appearance, but it is more difficult to keep clean. It is also very hard to drill or cut.

A newer material recently developed for switchboard panels, and known as **ebony asbestos,** has a number of very important advantages for this work. It is made of a composition material in which asbestos fibre and electrical insulating compounds are mixed and formed under great pressure into smooth-surfaced panels.

This material has a beautiful natural black finish, is lighter in weight, and has better insulating qualities and mechanical strength than either slate or marble. In addition to these advantages, ebony asbestos is also much easier to drill and cut, which makes it easy and economical to install.

Steel panels are also coming into use for switchboards, and have the advantage of great strength and durability. The switchgear on steel panels must, of course, be insulated from the metal at all points.

67-A. GENERATOR AND FEEDER PANELS

The common panel-type switchboards are usually made about ninety inches high, and as wide as necessary to provide the required space for the equipment needed. They are practically always built up in vertical sections or panels, each of which is used for the control of separate circuits. Panels of greater width are used for the main circuits or generator circuit control, and sub-panels of narrower width are used to control the separate feeder circuits, which supply the energy to the various lines or power circuits controlled from the switchboard.

Fig. 59 shows two generator panels on the right, and six feeder panels on the left. Note the difference in the size of the switches and circuit breakers on the main panels and sub-panels. By referring to this same figure, you will also note that each vertical panel is divided into three sections. This type of construction facilitates repairs and changes of certain equipment, without disturbing the rest of the equipment on that panel.

For example, if the switches on a panel are to be changed to others of different size or type, the sec-

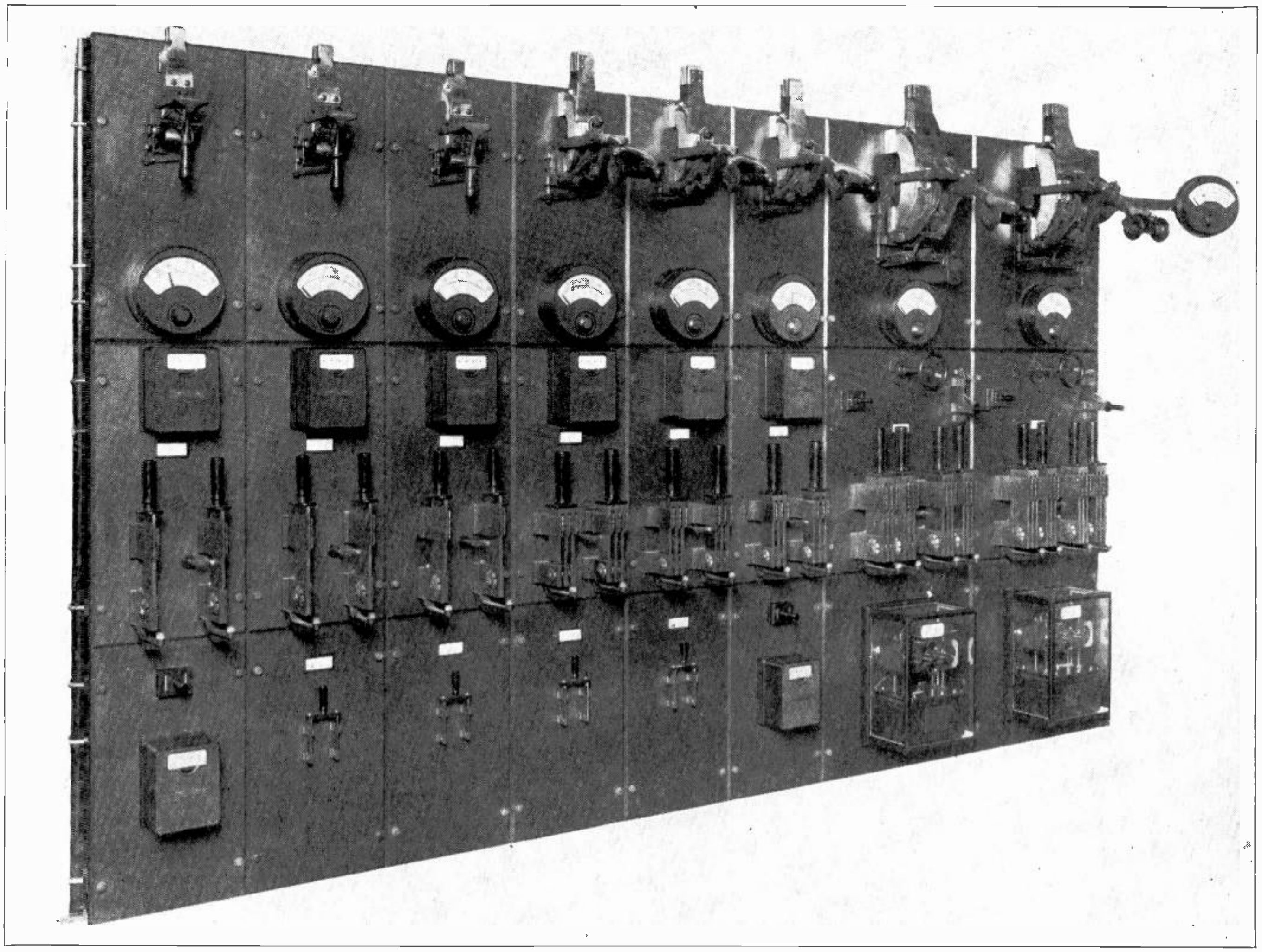

Fig. 59. This photo shows a modern panel type switchboard equipped with knife switches, meters, and circuit breakers. The two large panels on the right are the main generator panels and are equipped with field rheostats and instrument switches and much larger circuit breakers. The six smaller panels on the left are feeder or distribution panels. Examine all the parts and details of construction of this board very carefully, and refer to this figure frequently while reading the accompanying pages.

tion containing them can be removed and a new one drilled and inserted. It is not necessary to disturb the other two sections, or to leave unsightly holes in the board where the old switches were removed.

Sectional construction of panels also reduces the danger of cracked panels which might result from mechanical strains or vibration if larger single panels were used.

Switchboard panel material can be obtained in thicknesses from ½", for very small boards for light duty, to 2" or more for large heavy-duty boards. These panels are usually beveled on the corners of the front side, for better appearance.

68. SWITCHBOARD FRAMES

Switchboard panels are commonly mounted on either angle iron or pipe-work frames.

Where angle iron is used, it should be of the proper size to give the required strength and rigidity for proper support of the panels and switchgear. The board should not bend or vibrate noticeably during operation of heavy knife-switches or circuit-breakers.

Angle iron of 1½" to 3" is commonly used. It can be cut to proper length by means of a hack saw, and drilled for the bolts with which the panels are attached, and also for the bolts which hold the angle irons of adjoining panels together.

Fig. 62 shows how the panels should be bolted to the angle irons at "h," and the method of bolting the angle irons together at "h2". The panels should be carefully marked for drilling, so they will line up neatly and give the proper appearance when finished.

Short bolts of the proper length, with washers and nickle-plated cap nuts, can be used to provide good appearance of the front surface of the board.

These bolts and nuts should be tightened sufficiently to hold the panels securely, but not tight enough to crack the corners of the panels.

The bolt holes can be drilled in the panels with ordinary metal drills used in a breast drill or an electric drill. Slate and marble are hard and should, therefore, be drilled slowly or the drill should be cooled while it is cutting. Ebony asbestos is very easy to drill; in fact, nearly as easy as hardwood.

The lower ends of the angle irons should have

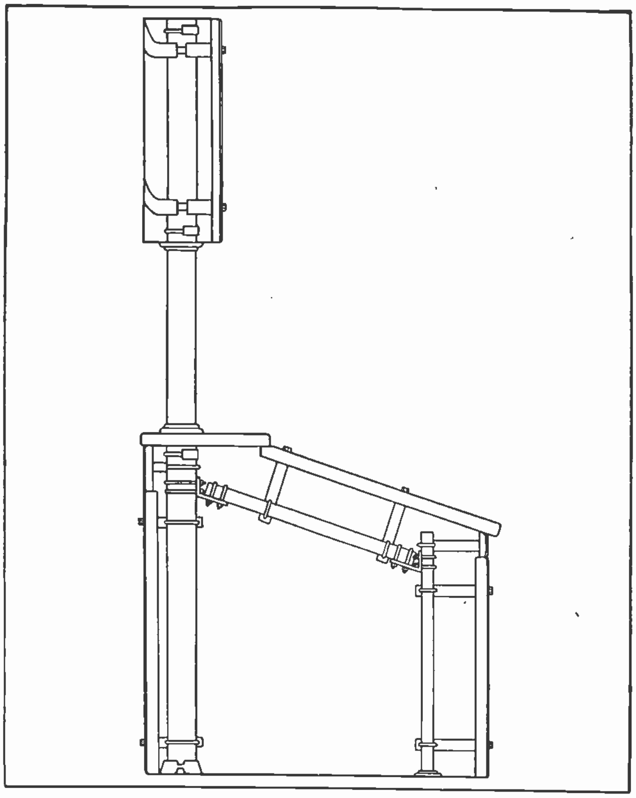

Fig. 60. The above diagram shows an end-view of a "bench-type" switchboard mounted on pipe frame work. This type of board is often referred to as "desk type".

"feet" bent in them or attached with bolts, for secure anchorage to the floor. The upper ends should be braced to keep the switchboard rigid.

69. PIPE FRAMES AND THEIR ADVANTAGES

Pipe-work frames are very convenient to install, as they do not require drilling as angle iron does. The pipe frame-work is held together by special clamps, as shown in Fig. 60. Fittings with holes for the panel bolts are also provided to clamp on the pipes. The pipes are attached to the floor with threaded floor-flanges.

Standard pipe sizes can be used; the common sizes being 1¼" to 2", or larger for very heavy boards. Special clamp fittings can be obtained for mounting bus insulators and various devices on the rear of the board. Other fittings are used for attaching brace pipes to secure the framework and board in a vertical position.

Pipe-work frames are very popular and are extensively used, as they provide a very flexible frame which can easily be adjusted to fit various panels and devices by merely sliding the clamp fittings. One of the pipes of the frame can be seen on the left end of the board shown in Fig. 59.

70. KNIFE SWITCHES. TYPES

Knife switches, used for controlling the various circuits on switchboards, are made in single, double, and three-pole types. The smaller and medium sizes are generally two or three-pole; but the larger ones are generally single-pole, for greater ease of operation. Three-pole switches or three single-pole switches are used to control the circuits of compound generators, the three poles being used in the positive, negative, and equalizer leads.

Three-pole switches are also used for circuits of the Edison three-wire system. Other D. C. circuits are usually two-wire, and they use either one two-pole or two single-pole switches.

Equalizer switches are sometimes mounted on small panels on pedestals near the generators, to eliminate the necessity of running equalizer busses

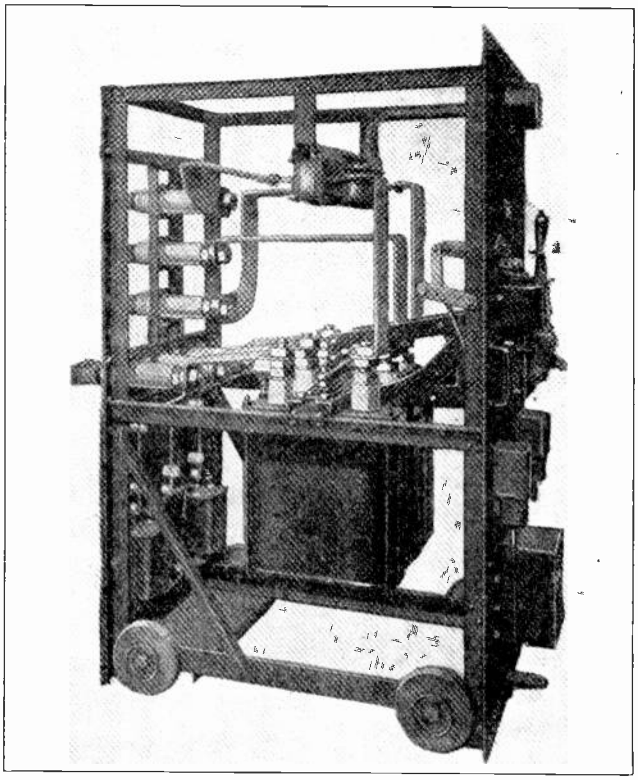

Fig. 61. This view shows a unit of a "truck type" switchboard on which the sections can be drawn out on rollers to make repairs and adjustments more conveniently.

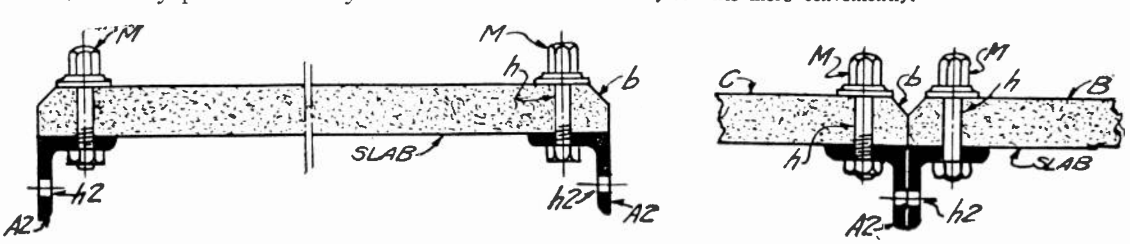

Fig. 62. The above sketches show the method of attaching switchboard panels to the angle iron frame work. Note how the panels are bolted to angle irons, and the angles bolted together between panels. Also note the type of bolts, nuts, and washers used with this construction.

to the switchboard. In such cases, the main panels for compound generators will also use two-pole switches.

71. CONSTRUCTION OF SWITCHES

Knife switches consist of three essential parts called the **blade, hinge,** and **clips**. The blades are made of flat copper bus bar material and are attached to the hinges by means of short bolts and spring washers. This fastening gives the required tension for good contact between the blades and hinges, and yet allows freedom of operation. See Fig. 63.

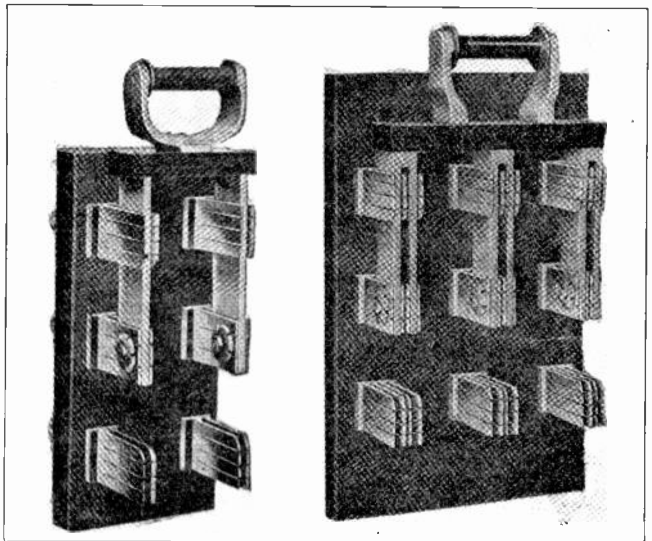

Fig. 63. Above are shown a double-pole and three-pole knife switch. Note carefully the construction of the switch plates, hinges, and clips.

Switch clips are made of two or more thin, springy pieces of copper, mounted in a block. The blades are inserted between these clips when the switch is closed. The clips are usually slotted to make them more flexible and allow them to make better contact with the blade of the switch. These details of construction can be observed by examination of the switches shown in Fig. 63, and also those on the switchboard in Fig. 59.

Switch blades are equipped with insulating handles and guards on their free ends. The hinges and clips usually have threaded studs of copper attached directly to them, for convenient mounting on the switchboard panels. Bus bars or cable lugs on the rear of the board are attached to these studs by means of extra nuts provided with them.

The switch at the left in Fig. 64 shows the studs and the nuts used both for holding the switch on the board and for attaching cable lugs or bus bars. This switch and also the double-pole switch on the right in this figure, are both of a newer type which has double blades and single clip prongs.

Knife switches on switchboards are practically always mounted with the blades in a vertical position and the clips at the top. This allows easier operation and prevents danger of the switch falling closed by gravity.

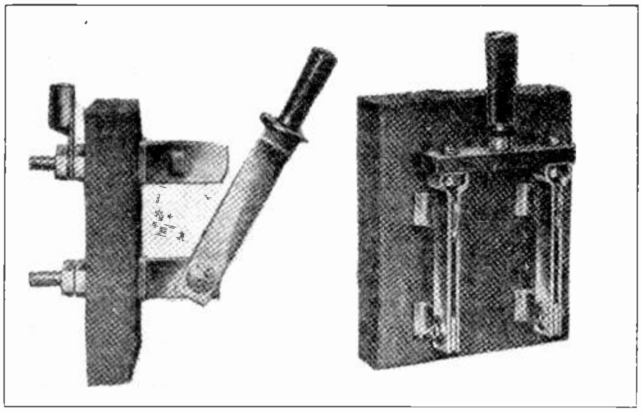

Fig. 64. Single-pole and double-pole switches of a modern type. Note the manner in which the hinges and clips are attached to the board and the method of making cable or bus connections to the studs on the back of the board.

72. SWITCH MOUNTING AND CURRENT RATINGS

In mounting switches on the panels, the hinges and clips should be carefully lined up so that the blades will fit well and make good electrical contact.

All knife switches are rated in ampéres according to the copper area of their blades and the contact area of clips and hinges. They are commonly made in sizes from 50 amperes to one thousand ampere capacity; and for heavy power circuits they are made to carry 6000 amperes or more.

You will note that a number of the switches on the right-hand side of the switchboard in Fig. 59 have multiple blades in each pole. This gives a much greater contact area between the blade surfaces and hinges and clips, and also allows air to circulate through the switches to cool them.

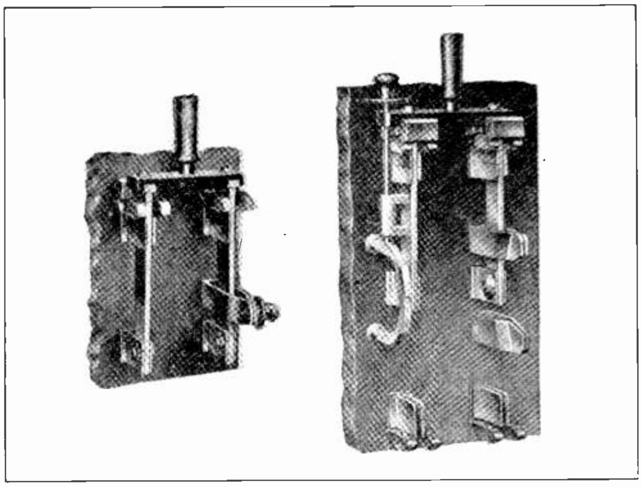

Fig. 65. A number of special types of knife switches are made with auxiliary clips and blades as shown above. These two switches are used as field discharge switches for generators.

Switches should never be loaded above their rated capacity in amperes for any great length of time, or they will overheat. Hinges or clips which are loose or poorly fitted will also cause overheating of the switch at these points. If switches are allowed to overheat too much, the copper will become soft and lose the springy qualities which are necessary for tight fitting of the clips. Overheated switches often cause the copper clips or blades to turn a bluish color. Switches that have been heated to this extent will probably need to be replaced.

73. CARE AND OPERATION OF SWITCHES

New switches should be carefully fitted and "ground in" before loading. "Grinding in" can be done by coating the switch-blades with vaseline or oil mixed with abrasive powder, and then opening and closing the switch a number of times. This grinds and polishes the sides of the blades and clips to make their surfaces perfectly parallel and provide a good contact between them.

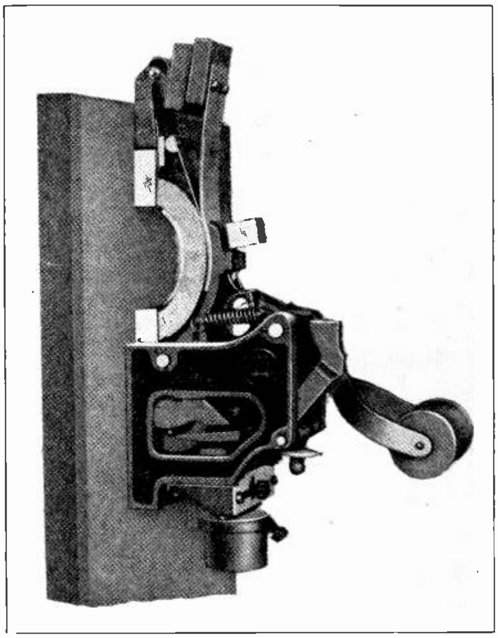

Fig. 66-A. This photo shows a common type of air circuit breaker in closed position. Note the manner in which the main contacts and auxiliary contacts connect with the stationary contacts on the panel.

Never open knife-switches under heavy load, if they have a circuit-breaker in series with them. Opening the switch under load will draw an arc at the point where the blades leave the clips. These arcs tend to burn and roughen the blades and clips, making the switch hard to operate and also destroying the good contact between the blade and clips.

Where circuit-breakers are provided they should always be tripped open first and the knife-switch opened afterward. This prevents arcing at the switch and is also much safer for the operator, as the arcs drawn by opening switches under heavy current load may be very dangerous.

Knife-switches should be kept lubricated with a thin film of petroleum jelly or light vaseline.

Special types of knife-switches, with snap-action blades operated by springs, are made for use in the shunt field circuits of generators. Field circuit switches often have auxiliary blades to close the field across a resistance just before the main blades open. Such switches are called **field discharge switches.** Two types of these switches are shown in Fig. 65. Their purpose is to prevent the setting up of high voltages by self-induction due to the collapse of the flux around the shunt field coils when this circuit is opened.

74. CIRCUIT BREAKERS

For opening heavy power-circuits in case of overload or short circuits, automatic circuit breakers are commonly used. These are divided into two general classes, known as **air circuit-breakers** and **oil circuit-breakers.** Air breakers will be described here and oil breakers will be covered in a later section.

An air circuit-breaker is a type of electric switch equipped with special contacts and a trip coil to open them automatically in case of overload on the circuit. Thus they provide for equipment the same protection as would be afforded by fuses.

For circuits which frequently require overload protection, circuit-breakers are much more suitable than fuses, as the breakers can be quickly closed as soon as the fault is removed from the circuit.

Circuit breakers are commonly made in single-pole, double-pole, and three-pole types, and for various current ratings, the same as knife switches are. Figures 66-A and 66-B show two views of a single-pole circuit-breaker. The view in 66-A shows the breaker in closed position, and in 66-B it is shown open.

The main current-carrying element or bridging contact is made of a number of thin strips of copper curved in the form of an arch and fitted closely together. This copper leaf construction permits the ends of this main contact to fit evenly over the surface of the two lugs, or stationary contacts, which are mounted in the switchboard and attached to the bus bars.

75. CIRCUIT-BREAKER OPERATION

When the breaker is closed by means of the

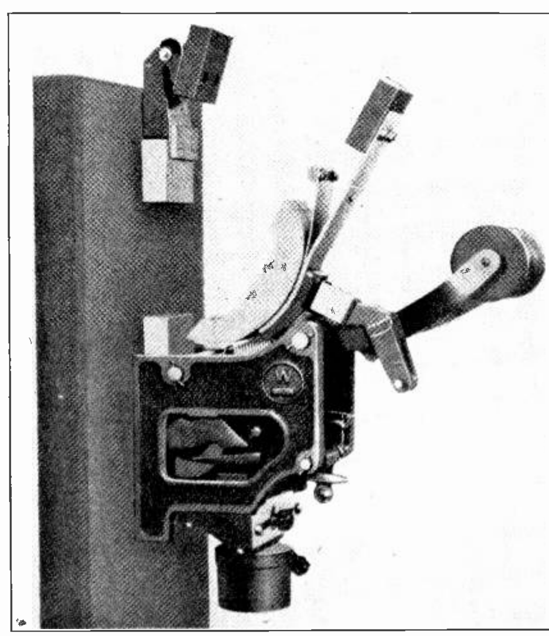

Fig. 66-B. This view shows the same circuit breaker as in Fig. 66-A, except that it is now in open position. Again note carefully the construction and position of the main contacts and arcing contacts. Also note the trip adjustment on the bottom of the breaker.

handle, a lever action is used to force the main contact tightly against the stationary contacts under considerable pressure.

Auxiliary arcing contacts and tips are provided above the main contact, as shown in the figures. The intermediate contact, or the one directly above the main contact, consists of the heavy copper spring with a removable copper tip. The top arcing contact on the movable element is carried by a long copper spring and has a removable carbon tip.

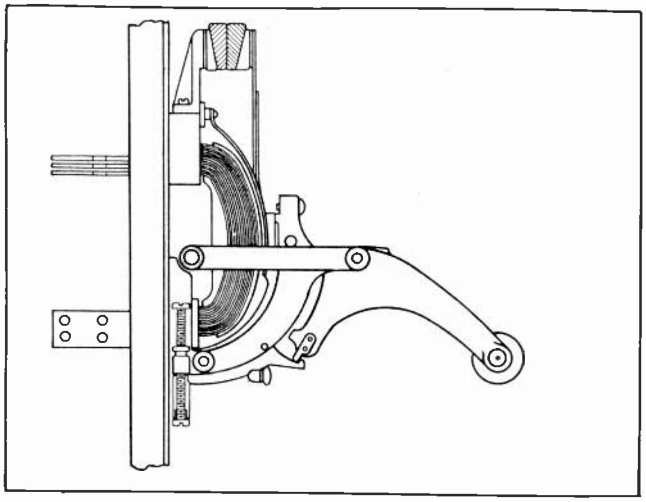

Fig. 67. This sketch shows a side-view of a circuit breaker in closed position and illustrates the copper "leaf" construction of the main contact. Note the copper stubs which project through the board for connections to bus bars.

When the breaker is opened, the main contact opens first and allows the current to continue flowing momentarily through the auxiliary contacts. This prevents drawing an arc at the surface of the main contact and eliminates possible damage to this contact surface, which must be kept bright and smooth and of low resistance, in order to carry the full load current without loss.

The intermediate contact opens next and it may draw a small arc, because the remaining circuit through the carbon tips is of rather high resistance.

The carbon contacts open last and the most severe arc is always drawn from these points. Carbon withstands the heat of the arc fairly well, and these contacts are easily and cheaply renewed whenever they have been burned too badly by repeated arcs.

Circuit-breakers of this type can usually be tripped open by means of a small lever or button, as well as by the automatic trip coil. When released they are thrown quickly open by the action of springs or gravity on their moving parts.

Fig. 67 is a sketch showing a side view of an air breaker in which can be seen the leaf construction of the main contact, and also the bus stubs to which the connections are made at the rear of the board.

When a circuit-breaker is closed the contacts close in the reverse order, the carbon tips closing first, intermediate contact second, and the main contact last. This construction and operation eliminates practically all arcing and danger of pitting at the ends of the main contacts. It is very important, however, to keep the auxiliary contacts and carbon arcing tips properly adjusted and occasionally renewed, so that they make and break contact in the proper order.

76. CIRCUIT-BREAKER TRIP COILS OR OVERLOAD RELEASE

Fig. 68 shows a single-pole and a double-pole circuit breaker which are both in closed position. The overload coils, or trip coils, can be seen on each of the breakers in this figure. These coils are of the series type and consist of a very few turns of heavy copper bar or cable, inside of which is located an iron plunger.

When the coil is connected in series with the line and breaker contacts, any overload of current will increase its strength and cause it to draw up the plunger. The plunger then strikes the release latch and allows the breaker to open.

An adjustment is provided for raising and lowering the normal or idle position of the plunger so that the breaker can be set to trip at different currents and loads. Trip coils of this type are known as **series-type overload release coils** and are commonly used on breakers up to 500 amperes capacity. The circuit-breakers shown in Figures 66-A and B have electro-magnets and armatures which trip the holding latches, and also an oil dash-pot to delay the opening of the breaker on light overloads. The adjustments for these devices can be seen below the breaker in these figures.

77. SHUNT TRIP COILS AND OVERLOAD RELAYS

For circuit breakers of 500 amperes and more, it is not usually practical to use series overload-coils, because of the large sized conductor which would be needed to carry the current.

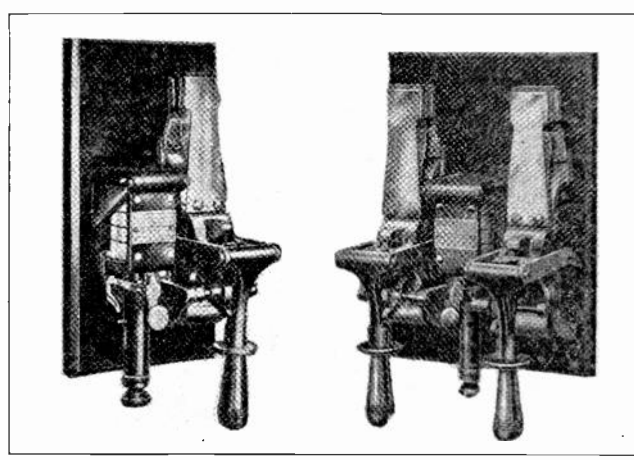

Fig. 68. Single-pole and double-pole, circuit breakers, showing the overload trip coils and their adjusting mechanism for operation of the breakers at different current loads.

On these larger breakers, **shunt trip coils are** used, and these coils are wound with a greater number of turns of small wire and are operated from an ammeter shunt. Shunt trip coils are not connected directly to the ammeter shunts, but are operated by a relay which obtains from the ammeter shunt the small amount of energy needed for its coil.

The greater the current flow through ammeter shunts, the greater will be the voltage drop in them. This voltage drop is usually only a few milli-volts, and as it is difficult to wind the shunt trip coils to operate on this small fraction of a volt, **overload relays** are generally used to close a circuit to these coils.

The overload relay is a very sensitive instrument, having a small coil designed to operate on a very low voltage of 50 to 100 milli-volts; and this coil is connected across the ammeter shunt.

The tension spring on the armatures of these relays is adjustable so the relay can be made to close its contact and energize the shunt trip coil on the breaker, at any desired current load within the range for which the relay and breaker are designed.

78. REVERSE CURRENT RELAYS

Some circuit-breakers are also equipped with reverse current protection to cause them to open in case of reversed polarity of a generator or reversed current flow in the line.

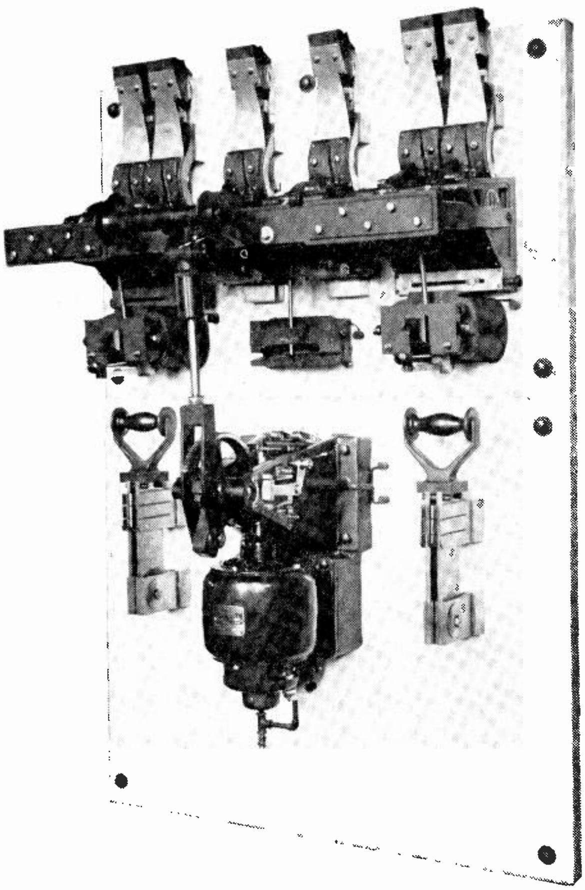

Fig. 69. Large, heavy duty circuit breaker equipped with a motor for automatic reclosing, after it has been tripped either by an overload, or by remote control.

Reverse-current relays are used to trip the breakers to obtain this protection. These relays have two elements or windings similar to the field and armature of a simple motor. One is called the **potential or voltage element**, and the other the **current element.**

The current coil or element is connected across the terminals of the ammeter shunt. The potential coil is connected directly across the positive and negative leads or busses and serves to maintain a constant field flux.

The direction of current through the current element or moving coil of the relay is determined by the direction of current through the ammeter shunt. When the current through the ammeter shunt is in the normal direction, the moving coil tends to hold the relay contacts open and keep the shunt trip-coil of the circuit-breaker de-energized.

If the current through the ammeter shunt is reversed this will reverse the polarity of the voltage drop across the shunt and send current through the movable element of the relay in the opposite direction. This reverses its torque and causes the coil to turn in a direction which closes the relay contacts and energizes the shunt trip-coil which trips the breaker.

These relays are also adjustable so they can be set to open the circuit-breaker at the desired amount of reversed current.

79. CIRCUIT-BREAKER CARE AND MOUNTING

Circuit-breakers are one of the most important pieces of switchgear and afford a great deal of protection to the electrical machinery on their circuits as well as to operators. They should be kept in good repair and adjustment, and should be frequently tested to be sure that they will open freely and quickly when necessary. The main contacts should be kept clean and well fitted, and arcing contacts should be renewed when badly burned. Operating springs and trip coils should be kept carefully adjusted.

Heavy-duty circuit-breakers require considerable force on the handle to close them, and also deliver quite a shock to the switchboard when they fly open. For this reason, switchboard panels carrying heavy breakers should be thick enough and sufficiently well braced to provide a rugged mounting for the breaker, and to prevent vibration of the board when the breaker is operated.

Fig. 69 shows a large circuit-breaker which also has a motor for automatically reclosing it. Such breakers can be equipped for remote control by the operator or for automatic reclosing by a time element or relay, after the breaker has been tripped open for a certain definite period.

80. INSTRUMENT SWITCHES

In addition to the knife switches and circuit-breakers, special switches are used for the switching and control of motor circuits. These may be of the **plug type, pull and push button type,** or **rotary button type.** These switches are mounted in openings drilled through the board, so that the handles or buttons project from the face of the board; and the switch element is mounted on the rear for con-

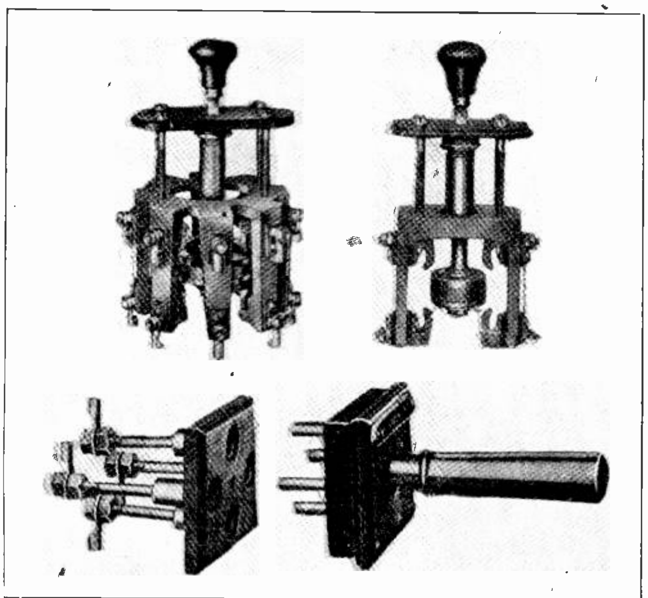

Fig. 70. Instrument switches of the above types are frequently used for changing the connections of various meters to different switchboard panels and busses.

venient connections to the smaller wires of instruments and relays.

Fig. 70 shows two instrument switches of the pull and push type in the upper view and one of the plug type in the lower view.

81. BUS BARS. MATERIALS AND MOUNTING

Copper bus bars are commonly used for connecting together the various switches, circuit breakers, and heavy power circuits on switchboards. Long busses are usually mounted on insulators attached to the rear of the switchboard frame or panels, while short lengths may be supported by the studs or bolts to which they connect.

Bus bars are generally run bare for the lower voltages up to 750 or, in some plants, even higher. Busses for higher voltages can be wrapped with varnished cloth or friction tape after they are installed.

Copper bus bar materials can usually be obtained in sizes from 1/8" to 1/2" in thickness, and from 1" to 4", or even 6" wide. When very heavy currents are to be carried, several bus bars are usually run in parallel and mounted with their flat sides vertical, as shown in the right-hand view in Fig. 71.

This arrangement of the busses allows air to circulate freely through them and helps to keep them cool. The view on the right in Fig. 71 shows two separate busses, "A" and "B", each consisting of three bars. One set is the positive bus and one is negative. Both sets are mounted in a base of insulating material, shown at "C", and supported by metal brackets attached to the switchboard frame.

The insulation used for mounting and spacing the bars can be hard fibre, slate, bakelite, or ebony asbestos.

In the left view in Fig. 71 is shown a single bus bar supported by a porcelain bus insulator.

Busses of opposite polarity and for voltages up to 750 should be spaced several inches apart wherever possible. When they are run closer together they should be well mounted and braced so they cannot easily be bent or vibrated together.

82. CONNECTING BUS BARS TOGETHER

Where bus bars are joined together, they can be fastened either by means of bolts through holes drilled in the copper or by bus clamps which do not require drilling the bars.

Fig. 72 illustrates the use of a common type bus clamp, consisting of two triangular pieces with three holes for the bolts which draw the parts of the clamp up tightly and grip the bars together. These clamps are very easy to install, as they do not require any drilling of the bars.

Copper bus bars can be cut to the proper length with a hack saw; and where bolts are used for connections the bars can be drilled with an ordinary metal drill.

Fig. 73 shows the method of connecting bus bars to the studs of switches or circuit-breakers, by means of two nuts and a short strip of bar connected to the main bus by a clamp. All joints and connections in bus bars should be made tight and secure, to avoid overheating when the current flows through them. Where the sections join the copper should be well cleaned of all dirt and oxide.

Copper bus bars of the smaller and medium sizes can be easily bent to various angles where necessary, but care should be used not to bend the corners too sharply and cause the bar to crack.

In locations where the busses are well ventilated, **it is common practice to allow about 1000 amperes per square inch of cross-sectional area of the bars.**

83. EXPANSION JOINTS OR LOOPS IN BUSSES

Where long busses are run, some allowance should be made for expansion and contraction with changes in temperature, or sufficient strains may be set up to warp the busses or crack the switchboard panels by twisting the studs.

A special loop or "U"-bend is sometimes put in a long bus to absorb this expansion in the spring of

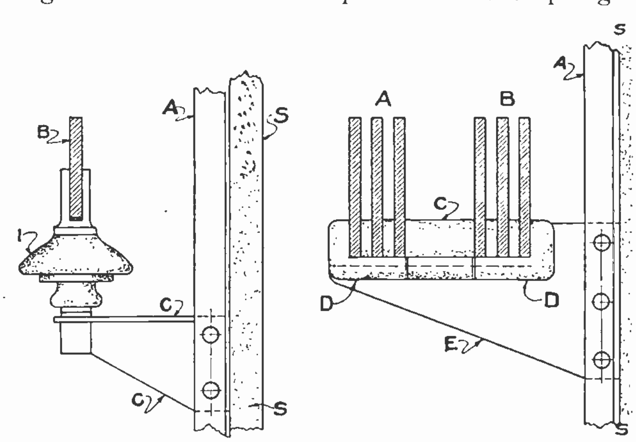

Fig. 71. The above diagrams show methods of mounting and installing bus bars on the back of switchboards.

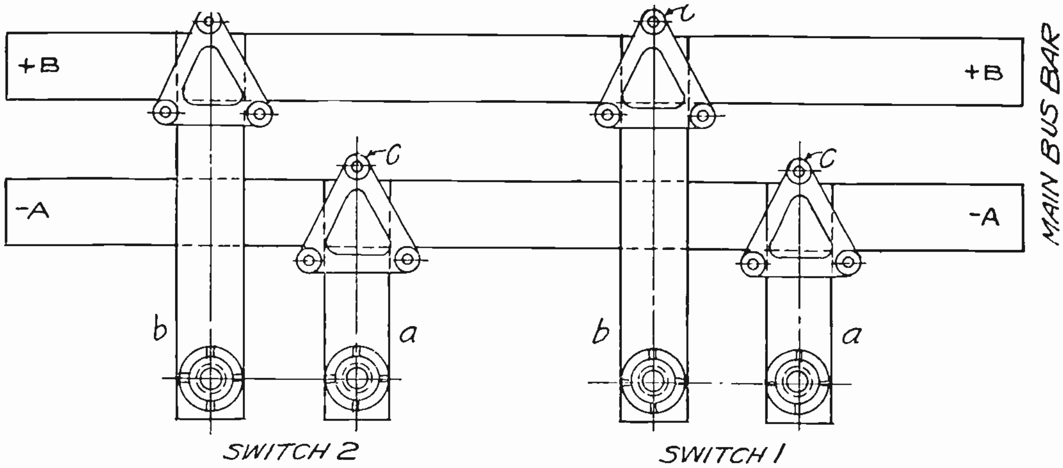

Fig. 72. Bus bars can be connected together by means of special clamps as shown above. These clamp pieces are held securely gripped to the busses by means of short bolts through the holes in their three corners. Clamps of this type save the trouble of drilling the copper busses.

the bend. In other cases, bus ends can be overlapped and held fairly tight with two bus clamps, but not tight enough to prevent the lapped ends from sliding on each other under heavy strains. One or more short pieces of flexible cable can then be connected around this joint to carry the current without heating. The cable ends should be soldered into copper lugs, and these securely bolted to the bus on each side of the slip joint.

84. SWITCHBOARD LAYOUT AND CIRCUITS

It is not a difficult matter to lay out and erect an ordinary switchboard for a small power plant or distribution center.

A plan should be laid out on paper for the required number of circuits. The desired switches, circuit-breakers, and meters for the control and measurement of the power, should be included in this sketch or plan.

After the load has been determined for the various circuits, the size of the switches and devices for the proper current ratings can be obtained from the manufacturer's specifications.

Panels can then be selected large enough to hold these devices in neat, uncrowded arrangement.

The simplest type of switchboard would at least contain switches for each of the main circuits and feeder circuits. There should also be on each of these circuits some form of overload protection, such as fuses or circuit-breakers.

On circuits of not over 500 amperes capacity and

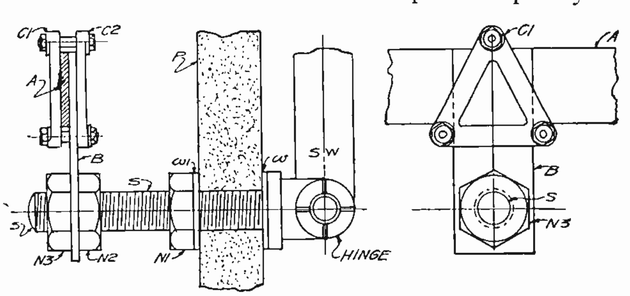

Fig. 73. Two views showing the method of connecting bus bars to the studs of switches and circuit breakers.

which are very seldom subject to overload, cartridge fuses will provide economical overload protection.

On heavy power circuits or any circuits which are subject to frequent overloads or occasional short circuits, circuit-breakers should be used. Circuit-breakers eliminate the replacement of fuse links and enable the circuit to be closed back into operation more quickly.

Usually it will be desired to measure the load in amperes on some of the circuits, if not on all of them. Ammeters of the proper size should be used for this purpose.

Where only one generator is used, one voltmeter may be sufficient to check the voltage of the main busses. Where several generators are operated in parallel, we will need one voltmeter for the main bus and probably one for each generator, in order to check their voltages before connecting them in parallel.

Sometimes one extra voltmeter is used for checking the voltage of any one of the generators which is being started up. This is done by the use of a voltmeter bus and plug switches for connecting the meter to whichever machine is being started up. A meter used in this manner is often mounted on a hinged bracket at the end of the switchboard, as shown in Fig. 59.

Wattmeters are often used to obtain instantaneous readings of the power in certain circuits. Watt-hour meters may be installed for showing the total power consumed per hour, per day, or per month, on any circuit.

In medium and larger sized plants, recording voltmeters and ammeters are often used to keep a daily record of the voltage and current variations. These instruments will be explained in a later section on D. C. meters.

85. SWITCHBOARD WIRING

Fig. 74 shows a wiring diagram for a simple D. C. switchboard with three panels, as shown by the dotted lines. The main generator-control panel is on the left, and contains the main switch, circuit-

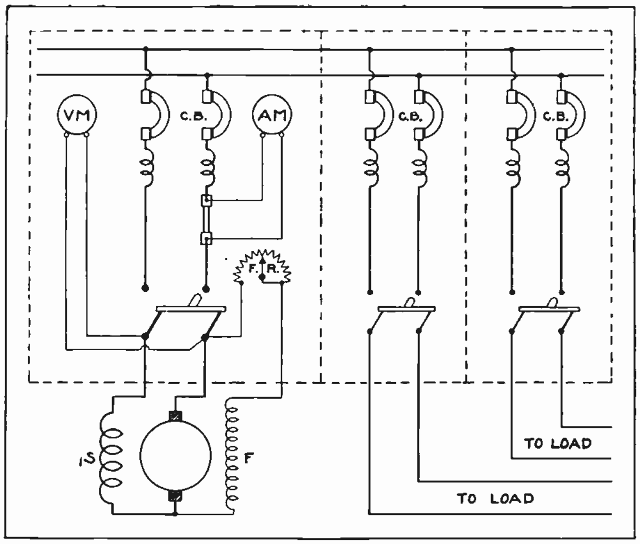

Fig. 74. The above diagram shows the wiring and equipment for a simple switchboard with one generator panel and two distribution panels.

breaker, voltmeter, ammeter and shunt, and the shunt field rheostat.

The two feeder panels on the right merely have switches and circuit breakers in each circuit.

Note that the circuit breakers and knife switches are in series in each circuit; so that, when the breaker in any circuit is tripped, there will be no current flowing through the switch.

The coils in series with each pole of the circuit-breakers are the series overload-release coils, which trip the breakers in case of an overload of current.

Note that the voltmeter is connected on the generator side of the main switch, so a reading of the generator voltage can be obtained before the machine is connected to the busses.

Fig. 75 shows a wiring diagram for a switchboard with two generator panels and two sub-panels or feeder panels. A number of feeder panels could be added to either side of this board if necessary.

Equalizer connections are shown for the generators, which are compound and are to be operated in parallel.

The circuit-breaker trip-coils are not shown in this diagram.

Circuits for switchboard instruments and meters which do not require heavy currents, are usually made with No. 12 or No. 14 switchboard wire, which has white colored slow-burning insulation. These wires can be held on the back of the board with small metal clamps and screws.

Examine the wiring and check the locations and connections of the various devices shown in Fig. 75.

86. LOCATION OF METERS AND SWITCHGEAR

Refer again to Fig. 59 and note the positions and arrangement of the various switchgear and devices on the board. Knife switches are usually mounted so their handles come about in the center of the board height, or a little lower, as this height is very convenient for their operation. Watthour and recording meters are frequently mounted along the lower panel-sections, underneath the knife switches.

Voltmeters and ammeters are usually placed above the knife switches, at about eye level or a little above, so they can be easily read.

Circuit-breakers are commonly placed at the top of the board, so any smoke or flame from their arcs cannot reach other instruments or blacken and burn the switchboard.

When air circuit-breakers open under severe overloads or short circuits, they often draw long, hot arcs. The flame, heat, and smoke from these arcs are driven upward by their own heat. Therefore, if meters or instruments were located above the breakers and close to them, they would be likely to be damaged.

Mounting the breakers at the top of the boards also places them up high enough so operators are not likely to be bumped or burned when the breakers fly open or, as we say, "kick out".

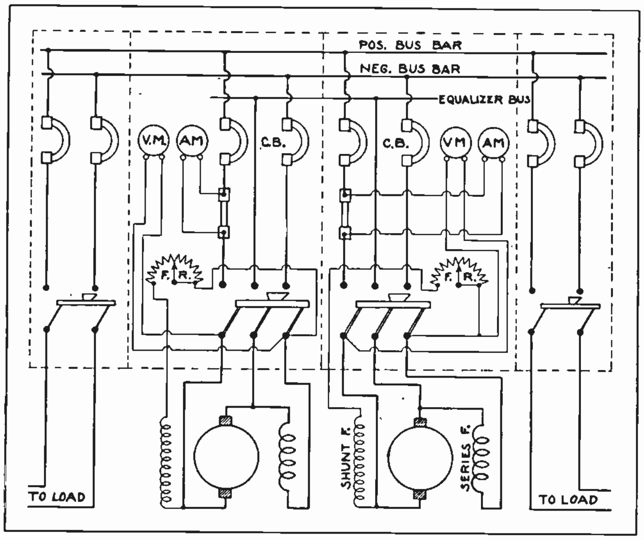

Fig. 75. Wiring diagram for a D. C. switchboard with two main generator panels and two or more feeder panels. Additional feeder panels would be connected to the board and busses the same as the two which are shown. Note carefully the arrangement of all of the parts and circuits shown in this diagram.

DIRECT CURRENT METERS

Electrical meters are used for accurately measuring the pressure, current, and power in various electrical circuits. There are a great number of types of meters, some of which are used only in laboratory work and others that are more commonly used in every-day work by the practical man.

These latter types are the ones which we will principally consider in this section. The meters most frequently used by electricians and operators are the **voltmeter, ammeter, and wattmeter.** These instruments are made both in portable types and for switchboard mounting.

87. TYPES OF METERS

The portable meters are used for convenient testing of machines and equipment wherever they are located, while the switchboard types are permanently mounted on switchboards for measuring the energy of certain circuits on these boards.

Voltmeters and ammeters are also made in recording types, which keep a record of their various readings throughout certain periods of time.

Wattmeters are divided into two general classes, called **indicating** and **integrating.**

The indicating instrument merely indicates the power in the circuit at any instant at which it is read. Integrating wattmeters, or watthour meters as they are commonly called, keep summing up the total amount of energy in kilowatt hours which is used throughout any certain period of their operation.

88. PARTS AND CONSTRUCTION OF D. C. METERS

Most meters operate on magnetic principles or use the magnetic effect of electric currents to produce the movement of the meter needle.

Ordinary D. C. voltmeters and ammeters, consist of a permanent magnet of horse-shoe shape which supplies a magnetic flux or field, a delicately balanced coil of fine wire which is rotated in this field, a pointer, scale, and case.

Fig. 76 shows the principal parts of a meter of this type, with the case or cover removed. The poles of the permanent magnet are equipped with pole shoes which have curved faces to distribute the flux evenly over the rotating element. In the center of the space between the magnet poles can be seen a round soft iron core which aids in concentrating and distributing the magnetic field over the space in which the coil moves. The needle is attached to this rotating or moving element so it will swing across the scale when the coil is rotated. This type of construction is known as the D'Arsonval, because it was first developed by a Frenchman named D'Arsonval.

Fig. 76-A shows a separate view of the moving coil with the needle attached. Also note the small coil-spring on each end of the moving coil. This coil is usually wound with very fine wire on a light-weight aluminum frame, the shaft of which is then set in jeweled pivots made of first-grade sapphires. These pivots make it possible for the coil to move with an extremely small amount of energy which makes the instrument very sensitive and accurate.

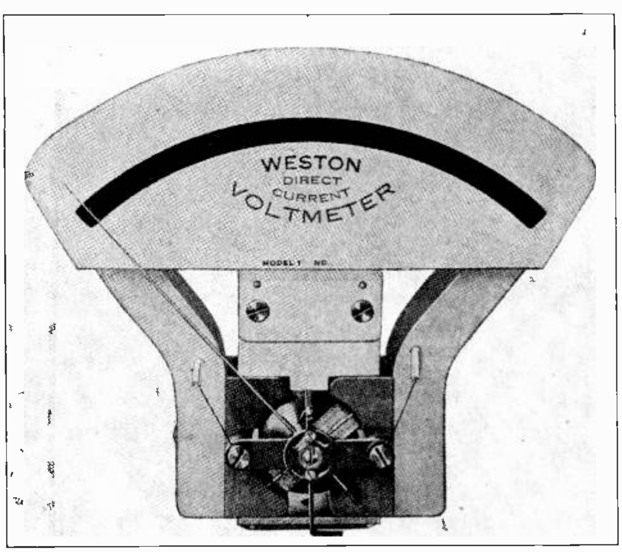

Fig. 76. The above view shows the important parts of a D. C. voltmeter. Note the horse-shoe magnet which provides the magnetic field in which the movable coil rotates. The movable coil with the pointer attached can also be seen between the magnet poles.

89. OPERATING PRINCIPLES OF D. C. VOLTMETERS AND AMMETERS

The operating principles of meters of this type are very similar to those of a D. C. motor. When a small amount of current is sent through the turns of the moving coil, it sets up around this coil a flux which reacts with the flux of the permanent magnet field and exerts torque to turn the moving coil against the action of the fine coil springs. The coil springs tend to hold the pointer, in normal or zero position, usually at the left side of the scale.

The greater the current passed through the moving coil, the stronger will be its flux; and the reaction between this flux and that of the permanent magnet will tend to move the needle across the scale, until the magnetic force is balanced by the force of the springs.

The amount of voltage applied to the coil will determine the amount of current flow through it. So the distance that the pointer is moved across the scale will indicate the amount of voltage or current in the circuit to which the meter is attached.

The same type of meter element can be used for either a voltmeter or ammeter, according to the manner in which the instrument is connected to the circuit to be measured.

The permanent magnets used with good-grade meters are made of the best quality of steel, and are usually aged before they are used in the meters. This aging process leaves them with a certain amount of magnetic strength, which they will retain for very long periods without noticeable weakening.

The pole shoes are made of good-grade soft iron to provide a low reluctance path for the flux of the permanent magnets. An additional stationary core of soft iron is often placed within the rotating coil, to provide a better magnetic path between the pole shoes, and to more evenly distribute the flux.

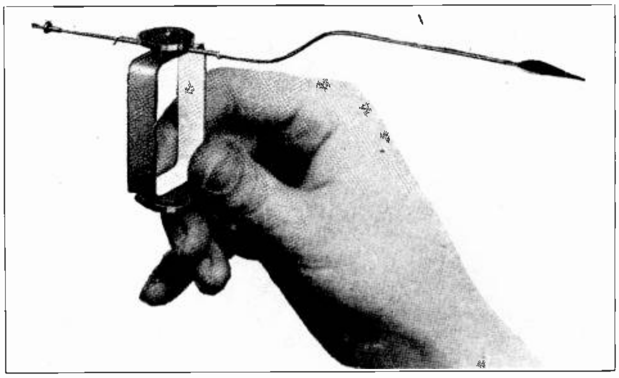

Fig. 76-A. An excellent view of the movable coil, pointer and spring of a D. C. meter.

90. DAMPING OF METER NEEDLES OR POINTERS

As the aluminum coil-frame is rotated through the flux of a meter of this type, small eddy currents are induced in the frame. These tend to set up a **damping** effect which slows or retards the rapid movement of the coil and needle, making the instrument more stable and preventing the needle from vibrating back and forth with small fluctuations in the voltage or current.

Some instruments have a light-weight air-vane attached to the needle, to provide a further damping effect and to prevent the needle from striking against the case at the end of the scale when sudden increases occur in the voltage or current of the circuit.

Small rubber cushions, or "stops", mounted on light wire springs are usually provided at each end of the scale to limit the needle travel and prevent it from striking against the case. These stops can be seen in Fig. 76.

Meter scales are usually printed in black on a white cardboard background, and are located directly behind the pointers, as shown in Fig. 77.

To obtain very accurate readings, some instruments have a mirror strip parallel to the scale and directly behind the pointer. In reading a meter of this type, one should stand in such a position that the pointer covers its own reflection on the mirror. This eliminates viewing the meter from an angle and perhaps reading the voltage or current at a scale line which is not directly under the pointer.

The instrument shown in Fig. 77 is one for switchboard use and is designed to be mounted flush with the surface of the board by setting the case in an opening cut in the switchboard panel. This meter is provided with a marker, or additional black needle with a round head, which can be set in any desired position on the scale by turning the button on the front of the case. This makes it easy to tell when the voltage of the generator or circuit has reached normal value, as the moving needle would then be directly over the marker.

91. CARE AND ADJUSTMENT OF METERS

Because of the delicate construction of the moving coils and the manner in which they are mounted in jeweled bearings, electric meters should be very carefully handled when they are being moved about; because, if they are dropped or severely jarred it may damage the mechanism and cause their readings to be inaccurate. Jarring also tends to weaken the permanent magnets. Meters should not be mounted where they are subject to severe vibration or mechanical shocks.

On many meters adjustments are provided by means of which the tension on the coil spring can be regulated by a small screw, thereby correcting any slight inaccuracies in the meter reading. Pivot screws should be kept tight enough to prevent too much end play of the shaft and coil, but never tight enough to keep the coil from moving freely.

92. VOLTMETERS

When meter elements of the type just described are used for voltmeters, the moving coil is connected in parallel, or across the positive and negative wires of the circuit on which the voltage is to be measured.

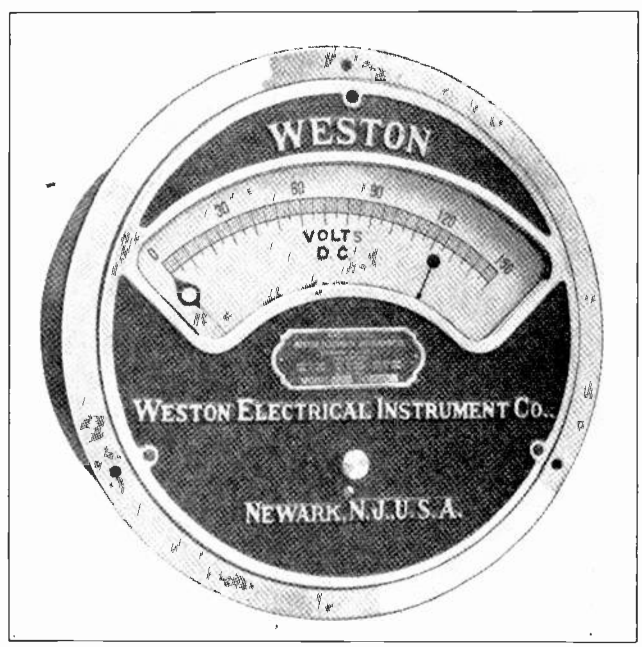

Fig. 77. Switchboard type voltmeter for mounting flush with the surface of the board. Note the stationary index pointer or marker, to indicate when full voltage is reached by the movable pointer.

It is difficult to wind a sufficient number of turns on the moving coil to have high enough resistance to stand the full line voltage on ordinary power and light circuits. For this reason, special resistance coils are connected in series with the moving coil element and the meter terminals, as shown in Fig. 78.

These resistance coils limit the current flow through the meter to a very small fraction of an ampere, and thereby allow the meter element to be constructed of light weight and as delicately balanced as required for accuracy. Voltmeter resistance coils can be located either inside the case or outside. Portable instruments usually have them located within the case, while with switchboard instruments the resistance coils are sometimes mounted on the back of the switchboard behind the instrument.

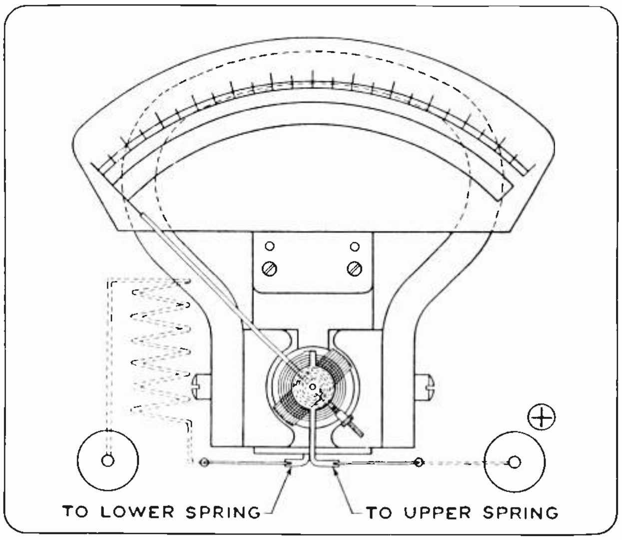

Fig. 78. This diagram shows the parts also the connections for a D. C. voltmeter.

By changing the number of these coils in series, or by changing their size and resistance, we can often adapt the same meter element for use on circuits of different voltages. When a meter is changed in this manner to operate on a different voltage, a different scale will probably also be required.

Fig. 79 shows a view of the inside of a voltmeter in which are mounted four resistance coils that are connected in series with a meter element.

Fig. 80 shows two types of external voltmeter resistance coils that can be used for mounting on the rear of the boards with voltmeters for switchboard use. With these resistance coils in series with the voltmeter element, it requires only a few milli-volts across the terminals of the moving coil itself to send through it enough current to operate the meter. Therefore, when the instrument is used without the resistance coils it can be connected directly to very low voltage circuits of one volt or less, and used as a milli-volt meter.

Whether it is used with or without the resistance coils, the strength of the flux of the moving coil and the amount of movement of the needle will depend entirely upon the voltage applied, because the current through the coil is directly proportional to this voltage.

Any type of voltmeter, whether for portable or switchboard use, **should always be connected across the circuit,** as shown in Fig. 81 at "A".

93. AMMETERS AND AMMETER SHUNTS

The construction and parts of an ordinary D.C. ammeter are the same as those of the voltmeter. When the instrument is used as an ammeter, the terminals of the moving coil are connected in parallel with an ammeter shunt, and this shunt is connected in series with the one side of the circuit to be measured, as shown in Fig. 81-B.

The ammeter shunt is simply a piece of low resistance metal, the resistance of which has a fixed relation to that of the ammeter coil. The load current in flowing through this shunt causes a voltage drop of just a few milli-volts and this is the voltage applied to the terminals of the ammeter coil.

In other words, the meter element simply measures the milli-volt drop across the shunt; but, as this drop is always proportional to the current flowing through the shunt, the meter can be made so that the load in amperes can be read directly from the meter scale.

This principle can be explained by another method, as follows: We know that electric current will always divide through any number of parallel paths which it is given. As the ammeter shunt is connected in parallel with the instrument coil and is of much lower resistance than this coil, the greater part of the load current passes through the shunt, and only a very small fraction of the current flows through the meter coil.

The use of a shunt in this manner eliminates the necessity of constructing meter coils large enough to carry the load current. This would be practically impossible on meters of this style for heavy duty circuits. Shunts also make possible the use of the same type of moving coil element for either ammeters or voltmeters.

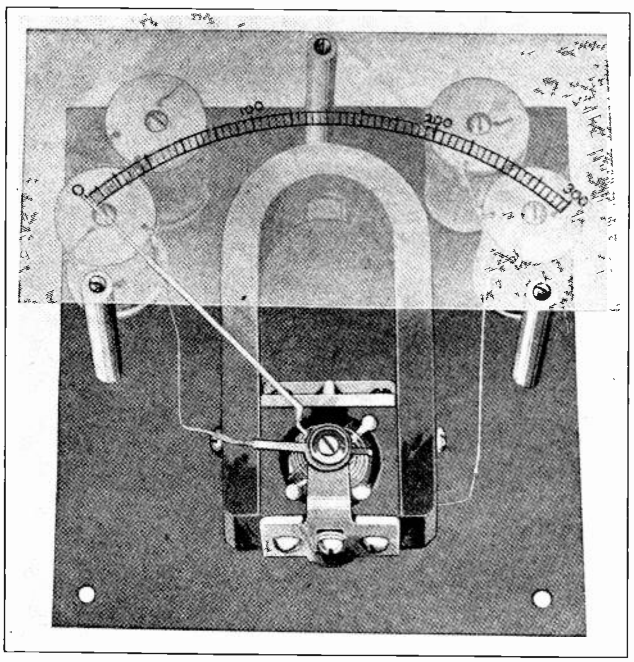

Fig. 79. The above view shows a D. C. voltmeter of a slightly different type, with the case removed to show the resistance coils which are connected in series with the movable element.

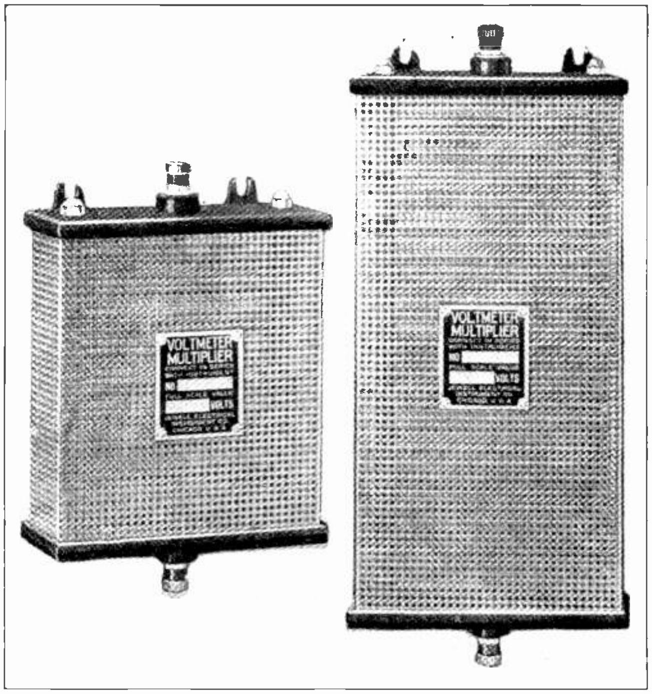

Fig. 80. External resistors for use with voltmeters and wattmeters. Resistors of this type are to be mounted outside the meter case, and usually on the rear of the switchboard

Ammeter shunts for portable instruments are usually mounted inside the instrument case; and for switchboard instruments on heavy power circuits, the shunt is usually mounted on the rear of the switchboard.

To obtain accurate readings on the meters, ammeter shunts should be made of material the resistance of which will not change materially with ordinary changes in temperature, as the shunt may become heated to a certain extent by the flow of the load current through it. The material commonly used for these shunts is an alloy of copper, manganese, and nickle, and is called "manganin". This alloy has a temperature co-efficient of almost zero; in other words, its resistance doesn't vary any appreciable amount with changes in its temperature. Manganin is used also because it doesn't develop thermo-electric currents from its contact with the copper terminals at its ends.

Ammeter shunts for use with D.C. ammeters are made in sizes up to several thousand amperes capacity. Fig. 82 shows several sizes and types of these shunts. Note the manner in which the strips of alloy are assembled in parallel between the bus connector stubs. This allows air circulation through the shunt to cool it.

94. CONNECTION OF AMMETERS AND SHUNTS

Remember that **ammeter shunts or ammeters must always be connected in series with the line** and **never in parallel.** The resistance of meter shunts is very low and if they were connected in parallel across positive and negative wires of a circuit, they would produce a severe short circuit, which on heavy circuits would be dangerous to the person connecting the meter and would at least blow the fuse and kick out circuit breakers. It would also probably burn out the meter or destroy the shunt.

Fig. 83 shows a common type of portable meter, such as is used in testing various electrical machines and circuits. The protective case and convenient carrying handle make these instruments very handy for use on the job. **Voltmeters, ammeters, and wattmeters of this type are very essential in any plant where a large number of electric machines are to be maintained.**

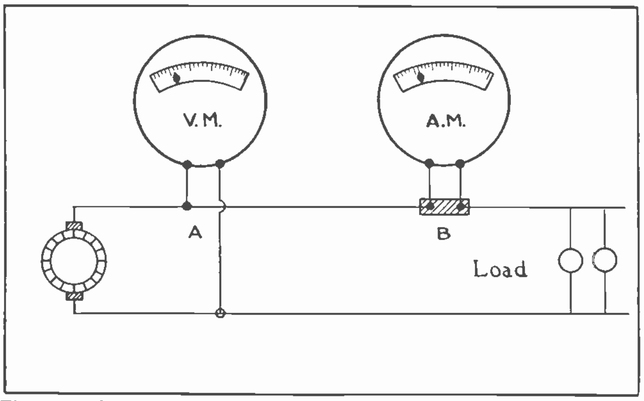

Fig. 81. This diagram shows the proper methods of connecting voltmeters and ammeters to electric circuits. Note carefully the manner of connecting voltmeters in parallel with the line and ammeters or their shunts in series with the line.

Testing the voltage and current of motors of different sizes will often disclose an overload or defective condition in time to prevent a complete burnout or serious damage to the machine windings.

Some portable instruments have two separate elements in the case and two separate scales, one for a voltmeter and one for an ammeter. Portable instruments of this type are very convenient for tests, but extreme care must be used to **be sure to connect the voltmeter terminals in parallel** and the **ammeter terminals in series** with any circuit to be **tested.**

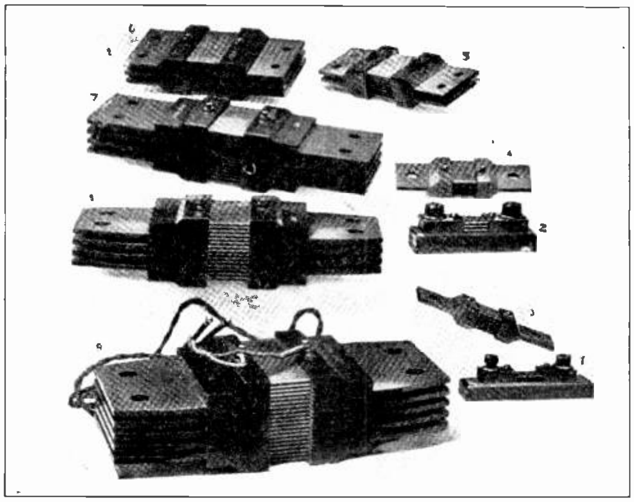

Fig. 82. The above photo shows several sizes and types of ammeter shunts which are generally used with ammeters where heavy loads are to be measured.

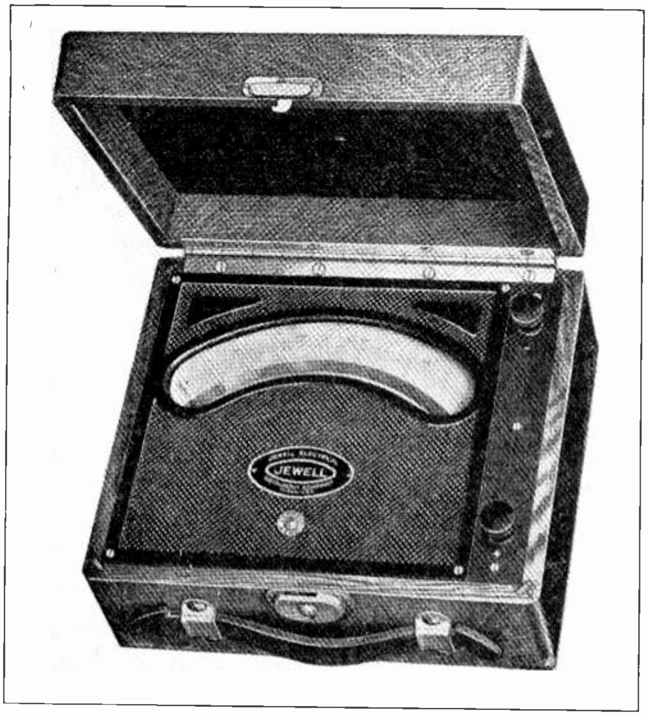

Fig. 83. Portable meters of the above type are very convenient and necessary devices for the practical electrician to use in testing various machines and circuits.

D. C. meters must be connected to the line with the proper polarity, and their terminals are usually marked "positive" and "negative", as shown in Fig. 84. If meters of this type are connected to the line with wrong polarity, the needle will tend to move backwards and will be forced against the stop wire or the meter case at the zero end of the scale.

The meter shown in Fig. 84 is another type of switchboard meter for surface mounting. This instrument doesn't require cutting any opening in the switchboard panel, since the meter is mounted flat against the front surface of the panel.

Fig. 85 shows another type of switchboard meter commonly used in power plants. Meters of this style often have the scale illuminated by electric lamps placed behind it. This makes the meter easier to read when the operator is some distance away, or working at the other end of the switchboard.

These meters are often mounted on a hinged bracket at the end of the switchboard so that they can be seen from any point along the board.

95. INDICATING WATTMETERS

Wattmeters, as previously mentioned, are used for measuring the power of circuits in watts. As this power is proportional to both the voltage and amperage of the circuit, wattmeters use two coils, one of which is known as the voltage or **potential** element, and the other as the **current** element.

The potential element is connected across the line, similarly to a voltmeter coil; while **the current element is connected in series with one side of the line,** similarly to an ammeter coil.

A diagram of the internal wiring and the connections of a wattmeter is shown in Fig. 86.

The potential coil is the movable element and is wound with very fine wire and connected in series with resistance coils, similarly to those used in the voltmeter. As this coil is connected across the line, the strength of its flux will always be proportional to the line voltage.

The current element is stationary and consists of a few turns of larger wire. As this coil is connected in series with the line, its strength will be proportional to the load and the current which is flowing. This current element supplies the field and takes the place of the permanent magnet used in voltmeters and ammeters.

As the turning effort, or torque, exerted on the movable coil is the result of reaction between its flux and the flux of the current element, the pointer movement will always be proportional to the product of these two fields and will, therefore, read the power in watts directly from the scale.

The coils of these instruments are not wound on iron cores but are wound on non-magnetic spools or in some cases the wires are stiff enough to hold their own shape in the coils. Wattmeters of this same design can be used on either D.C. or A.C., as they will read correctly on A.C. circuits if the reactances of both the moving and stationary coils are equal.

Wattmeters are designed for different amounts of voltage and current and should never be used on circuits with a greater amount of power in watts than they are rated for, nor circuits with higher voltage or heavier currents than the instruments are designed for.

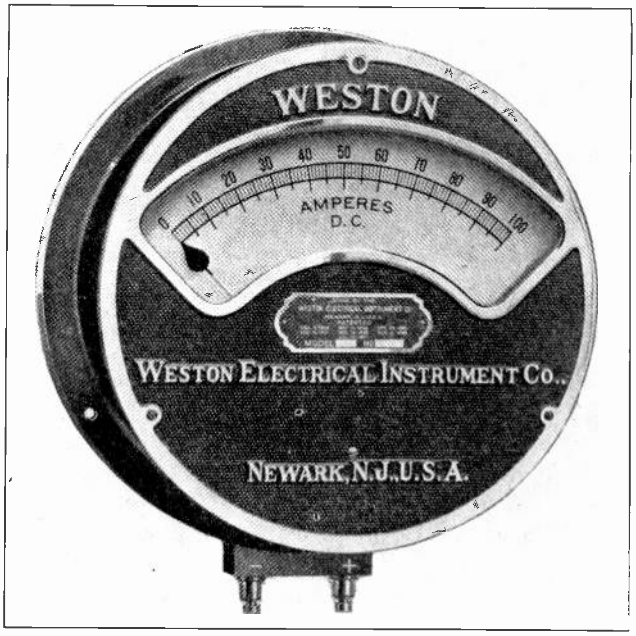

Fig. 84. Switchboard type ammeter for surface mounting. This meter does not require any large opening to be cut in the switchboard panel.

The terminals for the potential and current elements can be distinguished by their size, as those of the current element are usually much larger than those of the potential element. Extreme care should be used never to connect these in the wrong relation to the circuit, because if the current coil is connected across the line, a short circuit will result.

Fig. 87 shows the internal construction of a D.C. wattmeter. In this view the current coils, consisting of a few turns of heavy wire, can be plainly seen. The potential coil cannot be seen, however, as it is inside of the current coil.

96. WATTHOUR METERS

The common type of meter used in homes, factories, and power plants for measuring in kilowatt hours the total amount of power used during any certain period, is known as a **watthour** meter.

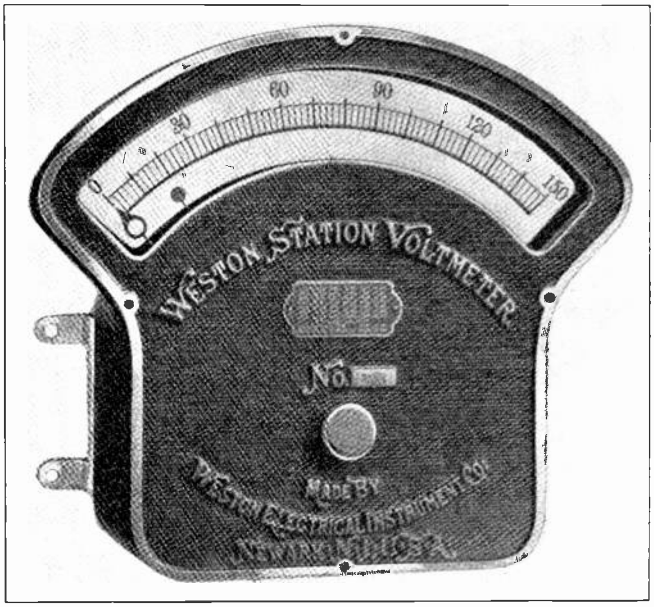

Fig. 85. The above view shows a large voltmeter of the type commonly used on power plant switchboards. The scale of these meters can be illuminated with lamps placed behind them so the meter can be read from any place along the board.

These meters have a current and potential element somewhat similar to those in the indicating wattmeter. The potential element, however, is allowed to revolve continuously, like the armature of a D. C. motor, as long as there is any load on the circuit line to which the meter is attached.

This element is not limited to a fraction of a turn by the coil springs, as in the case of indicating meters, but is mounted on a vertical shaft set in jeweled bearings and is free to revolve completely around, with the application of very small torque.

This rotating element is connected to a series of gears which operate the hands or pointers on the clock-like dials of these instruments. The current element consists of a few turns of large wire and is connected in series with the line, or in parallel with an ammeter shunt which is connected in series with the line. This stationary current coil provides a magnetic field similar to that of a D.C. motor, and in which the potential coil or armature element rotates.

97. PRINCIPLES OF WATTHOUR METERS

The potential element, being connected across the

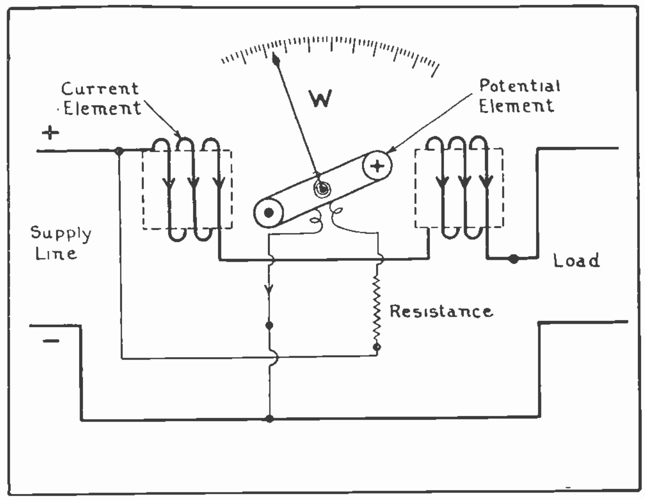

Fig. 86. This diagram shows the potential and current coils of a wattmeter. Note the manner in which each of these elements are connected in the circuit. The movable coil is shown in a sectional view so you can observe the direction of current through its turns and note how the flux of this movable coil will react with that of the current coils and cause the pointer to move.

positive and negative leads of the line, is always excited and has a very small current flowing through it as long as it is connected to the circuit. This coil usually has additional resistance coils placed in series with it, to limit the current flow to a very small value. Therefore it doesn't waste any appreciable amount of current by being permanently connected across the line.

As long as no load current is flowing through the line and the current element of the meter, there is no field flux for the flux of the potential coil to react with, and so it doesn't turn. As soon as load is applied to the line and current starts to flow through the stationary coils, it sets up a field which reacts with that of the potential coil, causing the latter to start to turn.

The greater the load of current, the stronger will

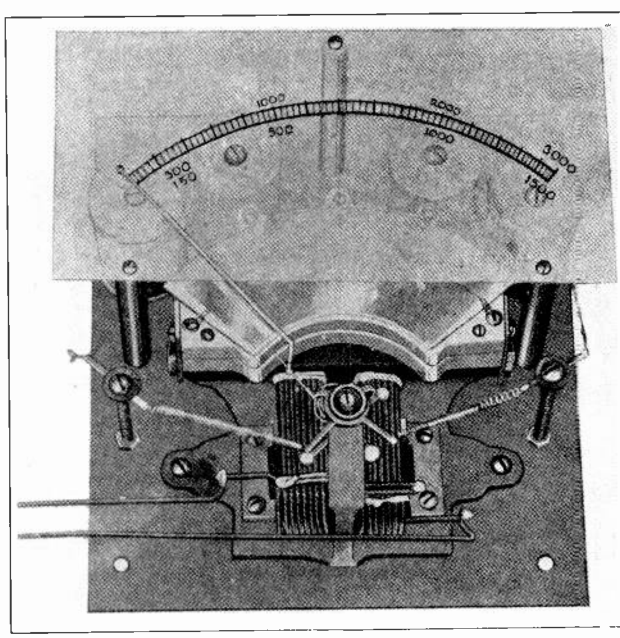

Fig. 87. This view shows the current coils, resistor coils, and general construction of a common type wattmeter.

be this field and the faster will be the rotation of the potential element or armature. This will cause the pointers on the dials to revolve faster and total up power more rapidly. The longer the load is left on the circuit, the farther these pointers will be revolved and the greater will be the total power reading.

98. CONSTRUCTION OF POTENTIAL AND CURRENT COILS

Fig. 88 shows three views of the armature or potential element of a watthour meter, both partly wound and completely wound. The coils of fine wire are wound on a drum or hollow ball of light weight non-magnetic material and are held in place by a coating of insulating compound. You will note that they are wound similarly to the coils of a simple D.C. motor armature. The leads of the coils are brought up to a very small commutator located on the top end of the shaft at the right.

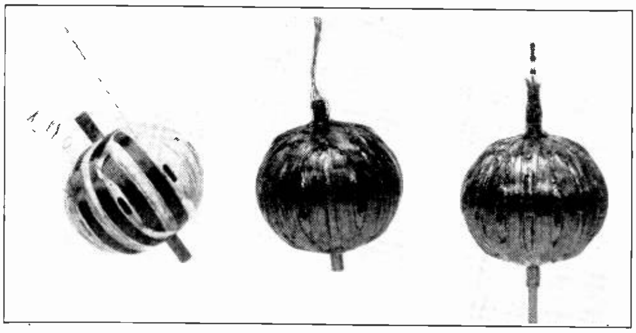

Fig 88. The above photo shows several potential or armature coils of watthour meters and illustrates the manner in which they are wound.

Fig. 89 shows both the current coils and potential coil of a watthour meter. The current coils are wound of heavy copper strip and are each divided in two sections. They are mounted close to the potential or rotating element, which can be seen just inside of them. You will note at the top of this figure the very small metal brushes mounted on wire springs and in contact with the small commutator to which the leads of the potential element are attached. Directly above this commutator is the small wormgear which drives the series of small gears that operate the dials. The brushes of the meter are connected in series with the proper resistance coils and then across the line wires, and they complete the circuit through the potential element, or armature, of the meter.

These brushes are commonly made of silver or some very good conducting material, in order to prevent resistance and voltage drop at the brush contact with the commutator.

99. DAMPING DISK AND MAGNETS

The speed at which the armature of the watthour meter will rotate depends upon the voltage applied to the potential element and the current flowing through the current element. Because of the very slow speed at which this armature revolves, its

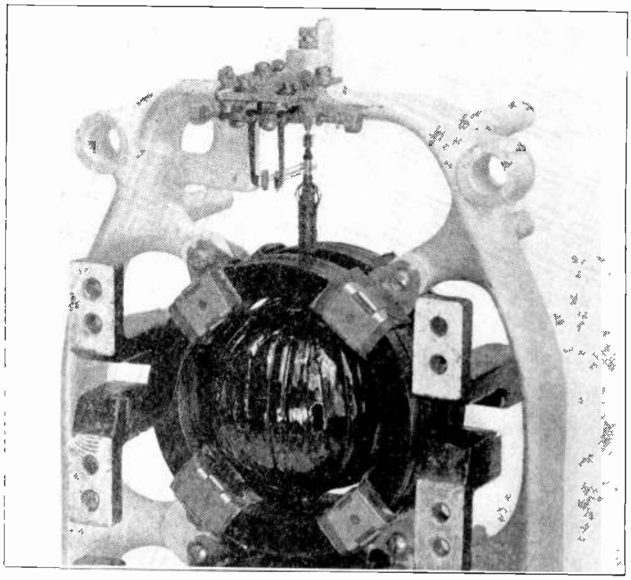

Fig. 89. This view shows the potential and current coils and also the commutator and brushes of a watthour meter.

speed is not regulated by counter-E.M.F., as armatures of direct current motors are.

In order to prevent over-speeding and to make the driving torque remain proportional to the power applied, the motor armature must have some damping or retarding effect to oppose the torque exerted by the magnetic fields. This counter-torque is obtained by mounting a thin aluminum disk upon the lower end of the armature shaft, and allowing it to rotate in the field of one or more permanent magnets of the horse-shoe type. This disk and the damping magnets can be seen in the lower part of the meter, shown in Fig. 90 with the cover removed.

As the aluminum disk is rotated, it cuts through the lines of force from the magnet poles and this generates eddy currents in the disk. The reaction between the flux of these eddy currents and that of the magnets tends to oppose rotation, just as placing a load upon a generator will produce counter-torque and require effort from the prime mover to turn it.

The induced eddy currents will be proportional to the speed of rotation of the disk and, as the flux of the permanent magnets is constant, the counter-torque exerted by the disk will be proportional to the product of the flux from these eddy currents and that from the permanent magnets.

When the load on the meter is increased, the speed of its armature increases, until the counter-torque developed by the disk just balances the torque exerted by the armature. In this manner, the armature speed is maintained proportional to whatever load is applied to the meter, causing the pointers on the dials to read the correct power in kilowatt hours.

This type of meter is often referred to as a watt-hour meter, but the gears and speed of most of them are so adjusted and of the proper ratio so that the readings will be in kilowatt hours, instead of watt hours.

100. ADJUSTING DAMPING EFFECT

The amount of damping effect produced by the disk can be adjusted by moving the poles of the permanent magnets in or out along the disk. If the poles are moved closer to the outer edge of the disk where it will cut their flux at higher speed, a greater amount of eddy current will be induced and cause a greater damping effect, and if the magnet poles are moved closer to the shaft where the disk is traveling at lower speed, the induced eddy currents will be less, and the damping effect will be reduced.

101. COMPENSATING COIL

No matter how carefully the armature of a meter of this type may be mounted, there is always a slight amount of friction to offer resistance to its rotation. Some of the energy produced by the meter coils will be required to overcome this friction and the friction of the gears on the dials.

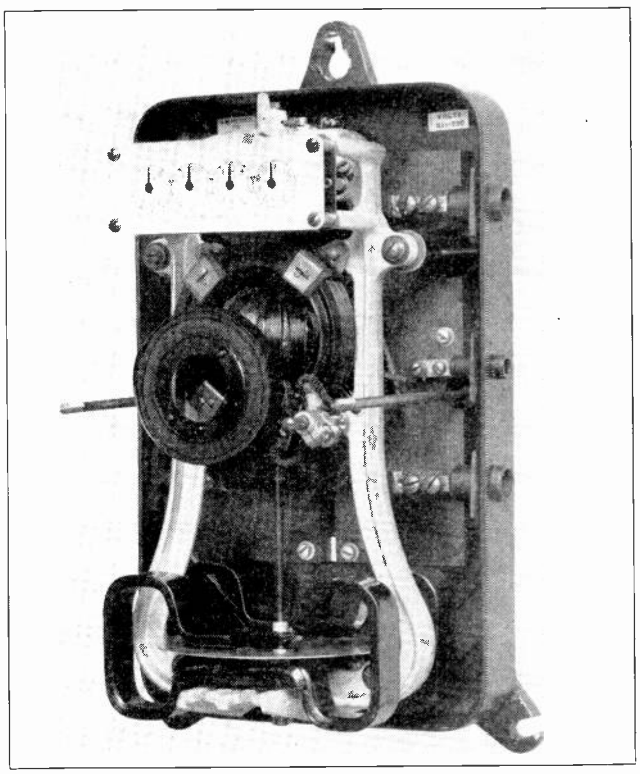

Fig. 90. Complete view of a KW-hour meter with the cover removed clearly showing the dials, current and potential coils, compensating coil, damping disk, and drag magnets.

In order to make a meter register accurately on light loads, this friction should be compensated for. This is done by means of a coil consisting of many turns of fine wire, connected in series with the armature or voltage coil of the meter. This **compensating coil** is mounted on an adjustable bracket in a position where its flux will react with that of the potential and current coils.

This coil can be seen in front of the current coils and armature of the meter shown in Fig. 90. By having this coil adjustable, it can be moved closer to or farther from the meter coils and its effect can be accurately adjusted so it will just compensate for the friction, and no more.

Sometimes these coils have a number of taps provided at various sections of the winding and also a small switch to shift the connections to include more or less of the turns of the coil. This also provides an adjustment of the amount of torque the coil will exert to overcome friction.

Fig. 91 shows the coils and connections of a D.C. kilowatt-hour meter. You will note in this figure that the friction compensating coil is connected in series with the armature and resistance coil, and this group are connected across the positive and negative line wires.

Current coils are connected in series with one side of the line so they will carry the full load current. The terminals of a watthour meter of this type are usually marked for the line and load connections, and these connections must, of course, be properly made so that the meter will run in the right direction.

102. WATT-HOUR CONSTANT AND TIME ELEMENT

A given amount of power in watts must pass through a watthour meter to produce one revolution of the armature and disk. For example, it may require a flow of energy representing 6 watt-hours, or the equivalent of 6 watts for one hour, to produce one revolution of the meter armature. This amount would be termed the **watthour constant** of the meter.

Knowing the number of watts per revolution, it only remains to get the total number of revolutions during a certain period of time, in order to know or measure the total amount of energy passed through the meter during that time. As each revolution of the armature is transmitted to the gears which operate the pointers on the dials, the total power in kilowatt hours can be read directly from these dials.

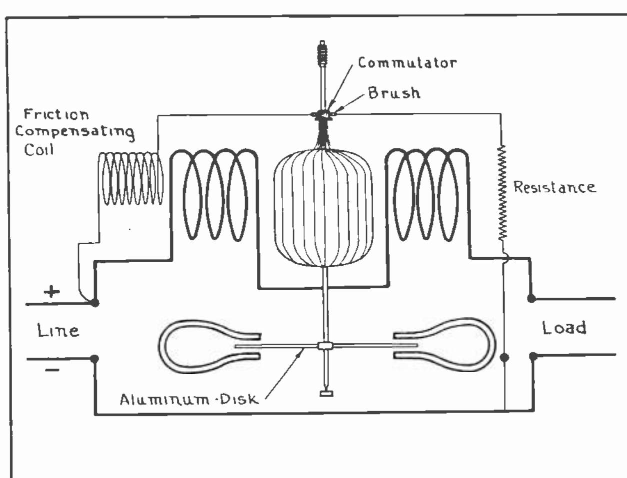

Fig. 91. This diagram shows the coils and circuits of a KW-hour meter and the manner in which they are connected to the line and load.

The operation of the gears and dials or registering mechanism is very simple. The worm-gear on the upper end of the armature shaft is meshed with the teeth of a gear which is the first of a row or chain of gears all coupled together. This gear has attached to it a small pinion which meshes with the teeth of the next gear and drives it at 1/10 the speed of the first one. This second gear, in turn, drives the third gear 1/10 as fast as it runs, and the third drives a fourth, the speed of which is again reduced to ten times lower than the third one.

Referring to Fig. 90, when the pointer on the right has made one complete revolution, the pointer on the next dial to the left will have travelled just one division or one-tenth of a revolution.

When the first pointer has made ten revolutions, the second one will have completed one revolution, and the third pointer will have moved one point. When the first pointer completes 100 revolutions, the second will have completed 10; and the third will have completed one revolution.

In this manner the first dial will have to make 1000 revolutions to cause the left-hand dial to complete one revolution.

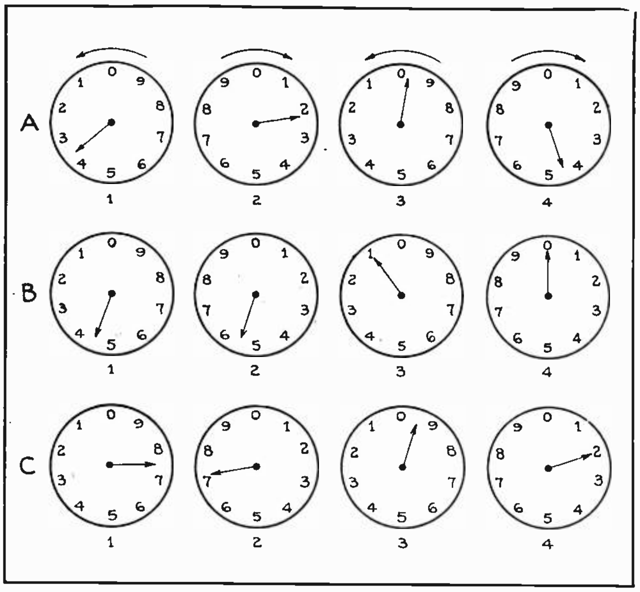

Fig. 92. The above sketches, A, B, C, show the dials of a kilowatt-hour meter in three different positions. If you will practice reading each set of these dials with the instructions here given, you will be able to easily and accurately read any KW-hour meter.

103. READING WATTHOUR METERS

By noting the figures at which the pointers stand, in order from left to right, we can read the kilowatt hours indicated by the meter. Some meters used on larger power circuits are adjusted so that their dials and pointers don't show the amount of power directly, but provide a reading which must be multiplied by some certain figure, such as 10, 20, or 50, to obtain the correct total reading. This figure is called a **constant** or **multiplier,** and it should be used whenever reading a meter of this type. This constant, or multiplier, is usually marked beneath the dials of the meter.

When reading kilowatt-hour meters, we should **always read the last number which has been passed by the pointer on any dial.** Some care is required in doing this until one has had enough practice to do it automatically. If each dial is not carefully observed, mistakes will be made; because **each adjacent pointer revolves in the opposite direction to the last,** as can be seen by the numbers marked on the dials shown in Fig. 92-A.

When the pointer is almost directly over one of the numbers, there may be a question as to whether the pointer has actually passed this number or is still approaching it. This should always be determined by referring to the next dial to the right to see whether or not its pointer has completed its revolution. If it has completed the revolution or passed zero on its dial, the pointer to the left should be read as having passed its number.

If the pointer to the right has not completed its last revolution, the one next to the left should not be read as having passed its number, even though it may appear to be beyond the number.

If the readings are carefully checked in this manner there is very little chance of mistakes.

On the second dial from the left in Fig. 92-A, the pointer revolves in a clockwise direction, and it might easily appear that it has passed the No. 2. By checking with the dial next to the right, however, we find that this pointer, which revolves counter-clockwise, has not quite completed its revolution or passed zero. Therefore, the dial at the left should still be read as No. 1. The correct reading for a meter with the pointers in the position shown in Fig. 92-A would be 3194 kilowatt hours.

The reading for the pointers in Fig. 92-B should be 4510 kilowatt hours. Here again the pointer on dial No. 3 appears to be on figure No. 1; and, by checking with dial No. 4, we find that its pointer is on zero or has just completed a revolution: so it is correct to read dial No. 3 as No. 1.

The reading for the set of dials in Fig. 92-C should be 7692. The pointer on dial No. 2 in this case appears to have passed No. 7; but, by checking with dial No. 3 to the right, we find its pointer has not quite completed its revolution; therefore, the dial to the left should be read as No. 6.

104. "CREEPING"

The armature of a watthour meter will sometimes be found to be rotating slowly, even when all load is disconnected from the circuit. This is commonly called **creeping** of the meter. It may be caused by a high resistance ground or a short on the line. The resistance of such a ground or short may not be low enough to cause the fuse to blow, and yet there may be a small amount of current flowing through it at all times.

If the load wires are entirely disconnected from the meter and the disk is still creeping, it may be due to the effects of stray magnetic fields from large conductors which are located near the meter and carrying heavy currents, or it may be caused by the fields from large electrical machines located near by.

For this reason, watthour meters, or for that matter any other electric meters, should not be located within a few feet of large machines, unless they are magnetically shielded, and they should be kept at least a few inches away from large conductors carrying heavy currents.

Large bus bars or cables carrying currents of several hundred or several thousand amperes set up quite strong magnetic fields around them for distances of several feet, and very strong fields a few inches away from them.

Sometimes a very small load such as a bell transformer or electric clock may cause the meter to rotate very slowly, but this is actual load and not creeping.

Vibration of the building or panel to which the meter is attached may sometimes be the cause of creeping. In some cases this may be stopped by proper adjustment of the compensating coil; or a small iron clip can be placed on the edge of the aluminum disk, if the clip does not rub the damping magnets as the disk revolves.

When this iron clip comes under the poles of the permanent magnets, their attraction for the iron will stop the disk and prevent it from creeping. As long as this clip doesn't touch the permanent magnets, it will not interfere with the accuracy of the meter; because its retarding effect when leaving the poles of the magnets is balanced by its accelerating effect when approaching the poles.

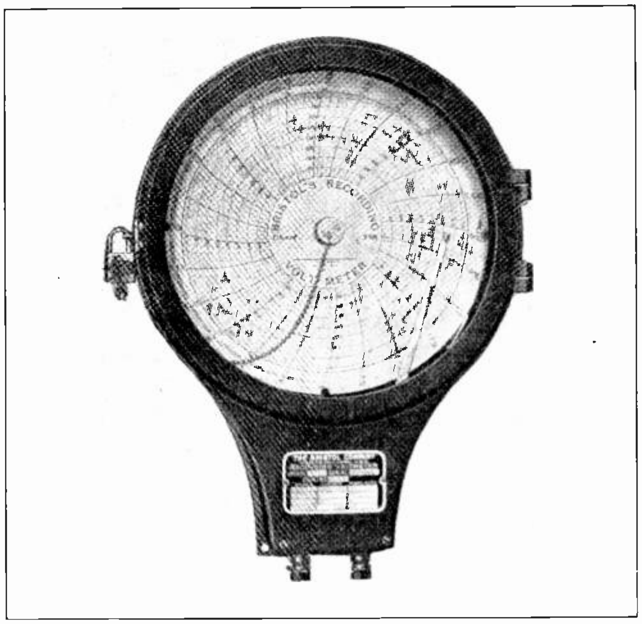

Fig. 93. Common type of recording voltmeter used for keeping an hourly and daily record of the voltages on the system to which it is attached.

105. TESTING KILOWATT-HOUR METERS

Kilowatt-hour meters can be tested for accuracy, or calibrated, by comparison with standard portable test instruments.

A known load consisting of a resistance box can be connected to the load terminals of the meter when all other load is off. Then, by counting the revolutions per min. of the disk and comparing this number with the revolutions made by the disk of a "rotating standard" test instrument, the accuracy of the meter can be determined.

When no standard load box or test instrument is available, a test can be conveniently made with a known load of several lamps or some device of which the wattage is known.

For this test the following formula should be used:

$$\frac{\text{WHK} \times 3600 \times \text{R}}{\text{W}} = \text{seconds}$$

In which:

WHK = the watt-hour constant marked on the meter disk.

3600 = number of seconds in an hour.

R = any chosen number of revolutions of the disk.

W = known load in watts which is connected to the meter.

For example, suppose we wish to test a meter which has a constant of .6, marked on its disk. We can connect a new 200-watt lamp, or two 100-watt lamps across the load terminals of the meter, after all other load has been disconnected. At the instant the lamp load is connected, start counting the revolutions of the meter and observe accurately the amount of time it requires to make a certain number of revolutions. Let us say it is 5 revolutions.

Then, according to the formula, the time required for the disk to make these 5 revolutions should be:

$$\frac{.6 \times 3600 \times 5}{200}, \text{ or } 54 \text{ seconds}$$

If it actually requires longer than this, the meter is running too slow. If the time required to make the 5 revolutions is less than 54 sec., the meter is running too fast.

Remember where to find this formula for future reference, as it may often be very convenient to use.

106. RECORDING INSTRUMENTS

In power plants or substations where large amounts of power are generated and handled, it is often very important to keep accurate records of the voltage, current, and power on principal circuits at all hours of the day and night.

Records of this kind will show any unusual variations in load or voltage and they are often the means of effecting great savings and improvements in the operation of power plants and industrial electric machinery.

It is usually not practical for an operator or electrician to keep constant watch of meters to obtain a record of their readings hourly or more often. Recording meters which will mark a continuous record of their readings on a paper chart or disk can be used for this purpose.

107. DIRECT-ACTING RECORDING METERS

One of the simplest types of recording instruments uses the ordinary meter element and has a case quite similar to that used for D. C. voltmeters or ammeters, and has a small ink cup and pen attached to the end of the needle or pointer. This pen rests lightly on a paper disk which is rotated once around every 24 hrs. by a clock-work mechanism inside the meter. See Fig. 93.

As the disk slowly revolves, the pointer pen traces on it a line which shows the movements of the pointer and the variations in voltage or current, whichever the instrument is used to measure.

The paper disks have on them circular lines which represent the voltage or current scale. By the position of the ink line on this scale the voltage or amperage at any point can be determined. Around the outer edge of the disk is marked the time in hours, so the readings for any period of the day can be quickly determined. Fig. 94 shows a disk from a meter of this type.

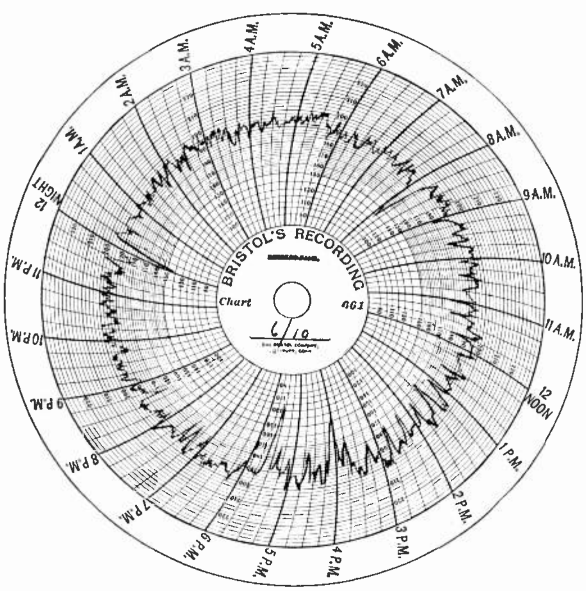

Fig. 94. Paper disk or chart from a direct acting recording meter. The irregular black line shows the voltage curve traced by the pointer and pen throughout each hour of the day and night.

Recording meters of the type just described are called **Direct-Acting** instruments. One of the disadvantages of meters of this type is that the friction of the pen on the paper chart does not allow the pointer and pen to move freely enough to make the meter very sensitive or accurate on small variations in the voltage or current. They also require frequent winding, replacing of charts, and refilling of the pen, but they are low in cost and very satisfactory for certain requirements.

108. RELAY TYPE RECORDING METERS

Another type of recording instrument in very common use is the **Relay Type**, which operates on the electro-dynamometer, or Kelvin balance, principle.

The Kelvin balance consists of a set of stationary coils and a set of movable coils. These coils can be seen at the top of the instrument shown in Fig. 95, which is a relay-type recording meter.

The thin moving coils are shown balanced between the larger stationary coils, and are equipped with a torsion spring which tends to oppose their movement in either direction.

Any change of voltage or current in these coils changes the repulsion or attraction between the fields of the moving and stationary elements, and will force the coils of the moving element up or down. This moving element then operates a set of relay contacts which close a circuit to the solenoids or small operating motor which moves the pen.

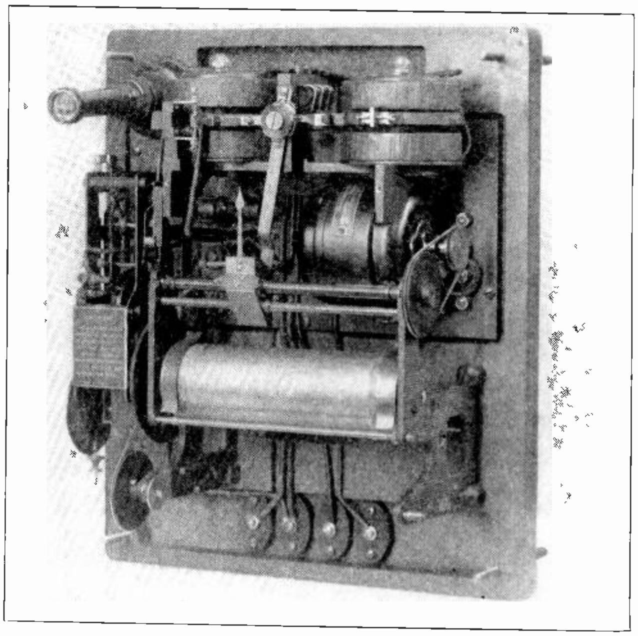

Fig. 95. This photo shows a complete recording instrument of the relay type with the cover removed. Note the stationary coils and balance coils at the top, and the roll for carrying the paper chart beneath the pointer.

The instrument shown in Fig. 95 uses a motor for the operation of the pen and pointer. The motor, which can be seen above the chart roll, revolves a worm shaft which moves the pen. The movement of the pen also readjusts the counter-torque spring on the movable coil so that it is balanced properly for the new position of the pen. This causes the balance coils to open the relay contacts and stop the motor; so the pen will remain in this position until another change of the voltage or current occurs.

The "clock" mechanism which drives the paper chart in this type of instrument is electrically wound and therefore does not require frequent attention.

Fig. 96 shows a recording instrument of this type, with the chart roll in place. This paper chart is continuous throughout the roll. So, as the roll travels and the pen moves sidewise across it, a continuous record of the voltage or power is kept. When the end of one roll is reached, a new one can be inserted.

Fig. 97 shows the connections for a recording meter of the type just described. Terminals 1 and 2 are for the motor circuit, and 3 and 4 are for the control circuit.

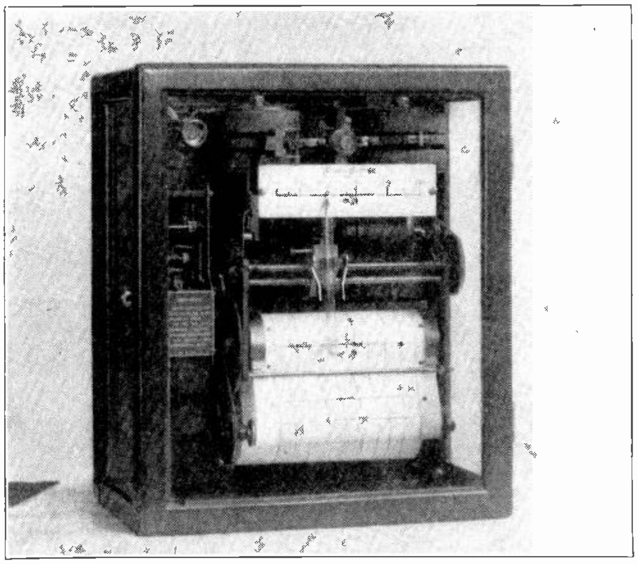

Fig. 96. This view shows the recording instrument which was shown in Fig. 95, with the paper chart in place. The glass ink cup and pen can be dimly seen attached to the lower part of the pointer.

109. LOAD DEMAND INDICATORS

Power and lighting loads which are of a steady or constant nature and do not vary greatly throughout the day are most desirable to power companies. Loads which have high "peaks" in proportion to the average hourly load, require the operation and maintenance of generating equipment which is sufficient for these peak periods, and may be either idle or lightly loaded at other periods. This tends to reduce the operating efficiency and economy in the power plant, and power companies will often give a customer lower rates per KW hr, on his power if his peak load is not over a certain percentage higher than his average load.

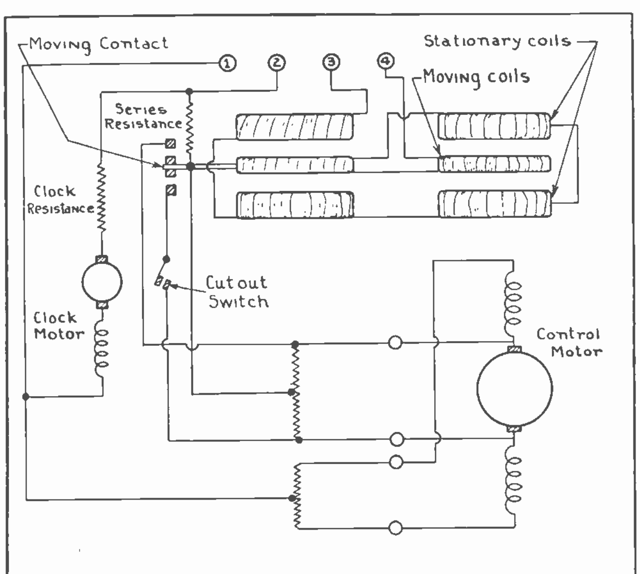

Fig. 97. This diagram shows the coils and winding of a recording meter such as shown in Figs. 95 and 96.

To determine the maximum load, or peak, for any period during the day or week, **Maximum Demand Indicators** are used. They are sometimes called "max. meters".

One type of demand indicator is the Wright maximum ampere-demand indicator, which operates on the thermal or heat expansion principle.

This instrument consists of a specially shaped sealed glass tube, as shown in Fig. 98. In this tube is sealed a certain amount of colored liquid, usually sulphuric acid, and a certain amount of air.

A resistance coil of platinoid metal is wound around the bulb as shown at "A" in the figure. This coil is connected in series with the line and load, or in parallel with an ammeter shunt. When current passes through the coil it causes it to become slightly heated and this heat expands the air in the bulb "A".

This expansion increases the air pressure and forces more of the liquid over into the right-hand part of the tube. If the liquid is forced high enough in this tube, some of it will run over into the small **Index Tube, "C"**.

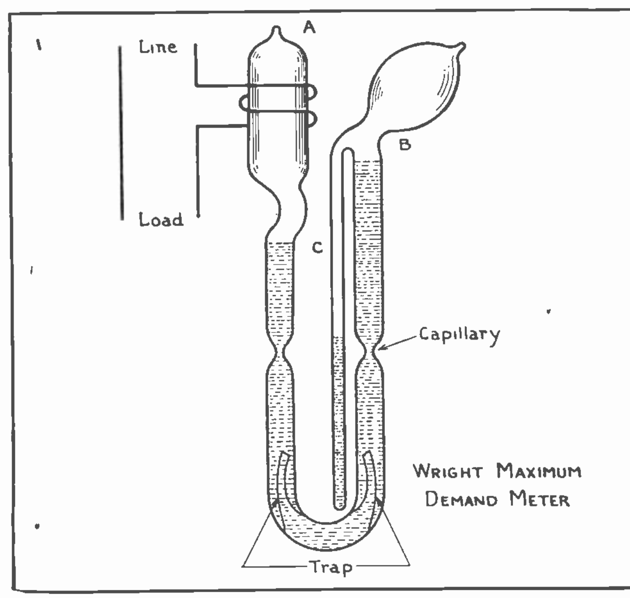

Fig. 98. This sketch illustrates the principle of a common type maximum demand meter which operates by expansion of the air in the bulb "A", when current is passed through the coil around this bulb.

As the heat developed in the resistance coil is proportional to the square of the current passing through it, the index tube "C" can be graduated or equipped with a graduated scale behind it; so the maximum current in amperes can be read from the height of the liquid in this tube.

A momentary increase in load will not register on an indicator of this type, because it requires a little time for the heat in the coil to expand the air inside the tube. This is a desirable feature, as it usually is not desired to measure peak loads that last only an instant.

A load increase which lasts for 30 minutes will register the full amount, or 100%, of the increase.

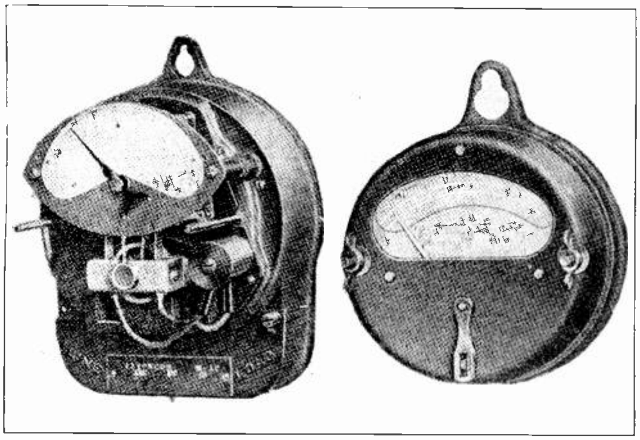

Fig. 98-A. Two types of demand meters using pointers operated by magnets and thermostats instead of liquid to indicate maximum load.

After a reading, this type of instrument can be reset by tilting the tube and allowing the liquid to flow back into tube "B".

Small, inverted, glass funnels are fastened inside the bottom of each side of the tube, to prevent the passage of air from one side of the tube to the other. These are called **traps.** When the tube is tilted to reset the indicator, these traps remain covered with liquid and prevent air from passing through.

Recording wattmeters or ammeters also serve as maximum-demand meters, as they show all load variations.

Another type of maximum-demand meter uses a combination of a wattmeter element and pointer and a watthour meter time element, to allow the wattmeter pointer to register only over certain time periods.

Some demand meters use a thermostatic strip to move the pointer as the strip is expanded and warped by the heat of the load current.

Fig. 98-A shows demand indicators of these types.

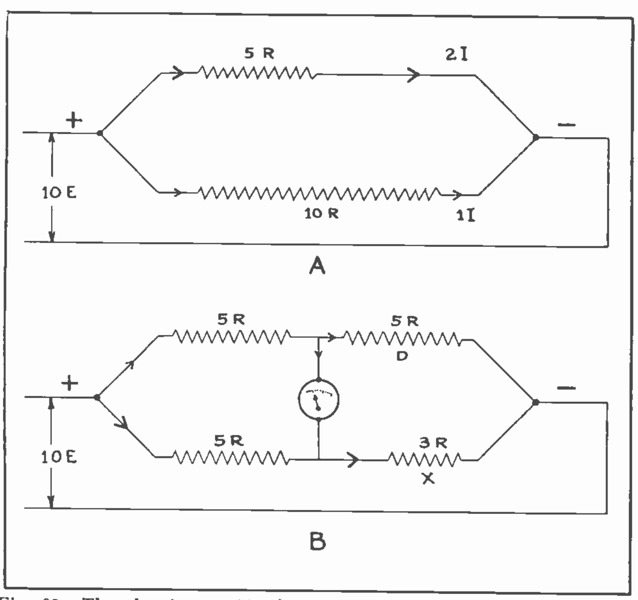

Fig. 99. The sketch at "A" shows the manner in which current will divide in inverse proportion to the resistance of two parallel circuits. At "B" is shown the manner in which current will flow through a galvanometer placed between four resistances, one of which is of a different value than the rest.

110. WHEATSTONE BRIDGE

This instrument is a very convenient device for measuring the resistance of electric circuits or devices, by comparison with standard resistances of known value.

You have already learned that electric current will tend to follow the path of lowest resistance, and will divide through parallel paths in inverse proportion to their resistance.

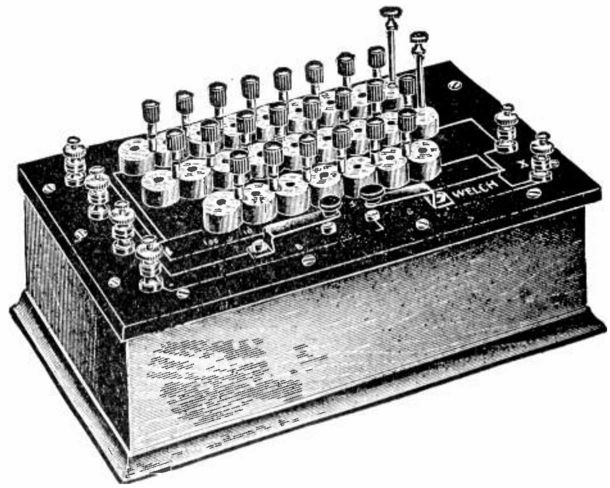

Fig. 100. Resistance box of a common Wheatstone bridge. Note the plugs which are used for varying the amount of resistance in the circuit.

For example, suppose we have one resistance coil of 5 ohms and one of 10 ohms connected in parallel, as shown in Fig. 99-A. If we apply 10 volts to the end terminals, 2 amperes will flow through the 5-ohm coil and 1 ampere through the 10-ohm coil.

Now let us connect a group of four coils as shown in Fig. 99-B. Here we have two coils of 5 ohms each in series on one path, and a 5-ohm coil and a 3-ohm coil in series on the other path.

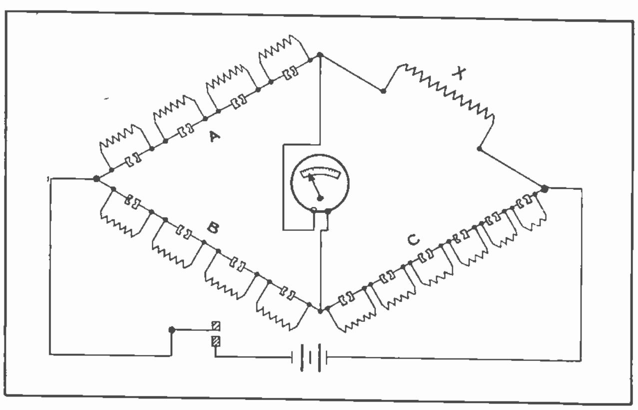

Fig. 101. This diagram shows the connections and principle of a Wheatstone bridge or resistance balancer. Note how the split metal sockets can be used to short out various resistance coils when a metal plug is inserted in these sockets. Study this diagram carefully while referring to the explanations on these pages.

If we now connect a sensitive galvanometer across the center of the paths between the coils, as shown, it will indicate a flow of current from the upper path to the lower when voltage is applied to the terminals of the group.

Tracing from the positive terminal to the center of the group, the resistance of each path is equal, but from this point on to the negative terminal the lower path or coil "X" has the lowest resistance. For this reason, some of the current tends to flow down through the galvanometer wire to the lower coil or easier path.

If we changed the coil "D" to one of 3 ohms, both sides of the circuit would again be balanced and no current would flow through the galvanometer.

On this same principle, if the resistance of coil "X" is not known, we can determine it by varying the resistance of coil "D" in known amounts until the galvanometer indicates zero, or a balanced circuit. We would then know that the resistance of coil "X" is equal to whatever amount of resistance we have in coil "D" to secure the balance.

111. OPERATION AND CIRCUIT OF WHEATSTONE BRIDGE

The Wheatstone Bridge operates on the same general principle just described. It consists of a box of resistance coils with convenient plugs for cutting coils of various resistance in and out of the balancing circuits. Fig. 100 shows the resistance box of a bridge of this type.

Some bridges have knobs and dial switches instead of plugs for switching the resistance units; and some have the galvanometer built in the top of the box, and the dry cells inside.

Fig. 101 shows a diagram of a common type of bridge and the method by which the coils can be left in the various circuits or shorted out by inserting metal plugs in the round holes between metal blocks attached to the ends of each resistance coil.

The coil or line of which the resistance is to be measured is connected at X. The circuits A, B, and C are called **Bridge Arms.** A and B are called **Ratio**

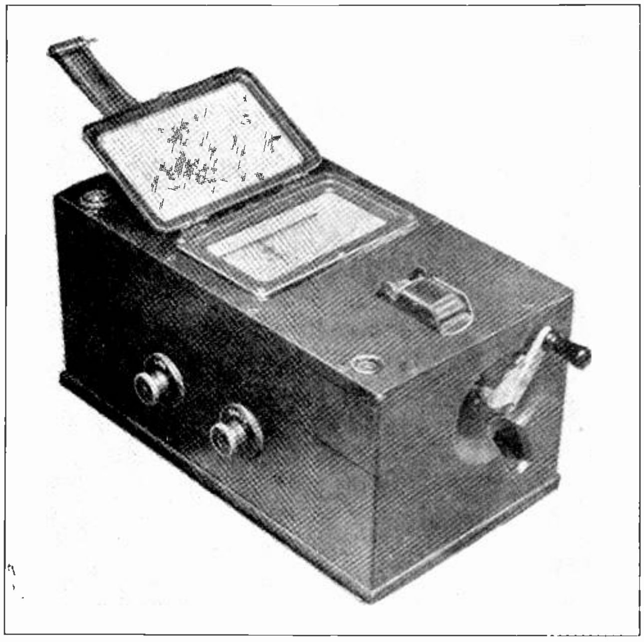

Fig. 102. The above photo shows a "Megger", or device used for measuring the resistance of insulation and high resistance circuits. This instrument contains its own D. C. generator as well as meter element.

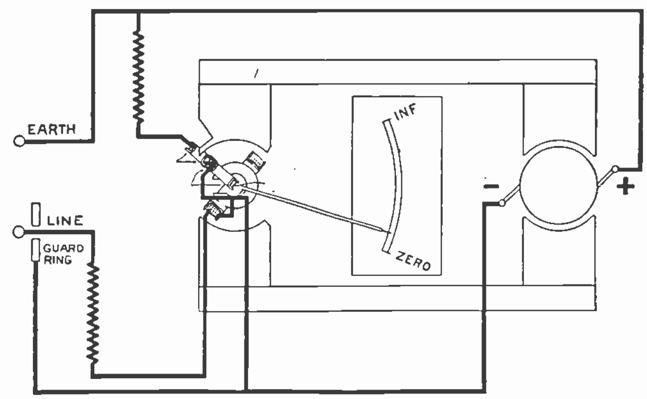

Fig. 103. Simple circuit showing the connections and principles of a "Megger". Note the arrangement of the D. C. generator armature and meter element at opposite ends of the magnet poles and the connections of this device to the line or test terminals.

Arms, or **balance arms**; and C is called the **Rheostat Arm.**

Arms A and B usually have the same number of resistor units of similar values in ohms. Arm C has a number of resistors of different values.

When the unknown resistance, X, has been connected in and the bridge arms so balanced that the galvanometer shows no reading when the button is pressed, the resistance of X in ohms can be determined by the use of the following formula:

$$X = \frac{A}{B} \times C,$$

In which:

X = resistance in ohms of device under test.
A = known resistance in ratio arm A.
B = known resistance in ratio arm B.
C = known resistance in rheostat arm C.

The Wheatstone bridge is a very convenient device for testing the resistance of coils or windings of electrical equipment; of lines, cables and circuits; and of the insulation on various wires or devices.

There are a number of types of bridges for resistance measurement, most of which are supplied with a connection chart and instructions for operation. So, with a knowledge of their general principles as covered here, you should be able to use and operate any ordinary bridge.

112. "MEGGER"

Another testing instrument frequently used by the practical electrician for testing the resistance of insulation on electrical machinery is known as a **Megger.** This name comes from the fact that this instrument is commonly used to measure resistances of millions of ohms; and a million ohms is called one meg-ohm.

The megger consists of a small hand-operated D. C. generator and one or more meter elements, mounted in a portable box, as shown in Fig. 102. When the crank is turned, the D. C. generator will produce from 100 to 1000 volts D. C., according to the speed at which the generator is rotated and the number of turns in its winding.

Normal operating voltage is usually from 300 to 500 volts, and is marked on the meter scale. Some of these instruments have a voltmeter to show the generator voltage, and an ohm-meter to indicate the insulation resistance of the device under test.

The terminals of the instrument can be connected to one terminal of a machine winding and to the machine frame. Then, when the crank is rotated the insulation resistance in meg-ohms can be read directly from the scale.

Fig. 103 shows the internal connections of a megger and the terminals for connections to the equipment to be tested. As the insulation of electrical machines or lines becomes aged, or in some cases where it has been oil or water-soaked, its resistance in ohms is considerably reduced. Therefore, **the resistance test with the megger is a good indication of the condition or quality of the insulation.**

Periodic megger tests of electrical equipment and records of the insulation resistance will often show up approaching trouble before the insulation breaks down completely and burns out the equipment.

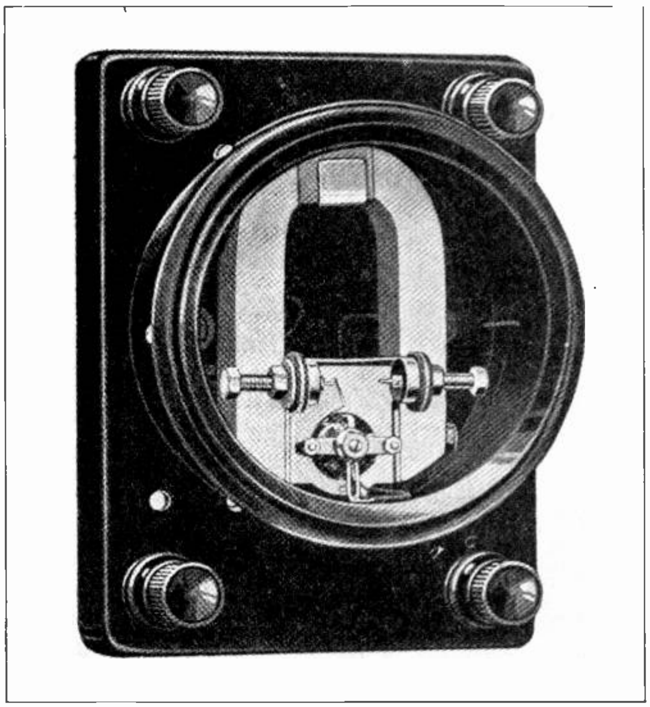

Fig. 104. Very sensitive relays such as shown above are commonly made with the same principal elements used in voltmeters' or ammeters. Relays of this type can be used to open or close various circuits at any set voltage or current values.

Either the Wheatstone bridge or the megger can be used to determine the approximate location of grounds or faults in cables and long lines, by measuring the resistance from the end of the line to the fault, through the cable and its sheath or the earth. Then, by comparing this resistance with the known resistance total of the line or with its resistance per foot or per 1000 ft., the distance to the fault can easily be calculated.

113. METERS ESSENTIAL IN ELECTRICAL WORK

A number of simple and practical tests of resistance can also be made with voltmeters and ammeters, and the use of ohms law formulas. By applying voltage of a known value to any device and accurately measuring the current flow set up by this voltage, we can readily calculate the resistance of the circuit or device by the simple formula:

$$R = \frac{E}{I}$$

While on the subject of meters, it will be well to mention that very sensitive relays are often made from regular meter elements, using a short armature or moving contact in place of the regular pointer or needle. Fig. 104 shows a relay of this type. In this figure you can see the short contact needle attached to the moving coil, and the adjustable contacts on each side of this needle.

By proper adjustment of the contacts of relays of this type, they can be made to close or open circuits when the voltage or current values rise above or fall below any certain values.

Keep well in mind the importance of ordinary electric meters in the work of any practical, up-to-date electrician, and remember that **great savings in power or equipment can often be made by the proper use of electrical meters and instruments.**

For testing the efficiency of machines, checking operations in power plants, inspection of electrical equipment, and for trouble shooting and fault location, electrical meters of the proper types are of enormous value.

The trained practical man should never overlook an opportunity to effect a saving or improve operation by the selection and use of the proper meters.

Changing Meters for Higher or Lower Readings

In certain cases an electrician may not have suitable meters for testing all of the various circuit voltages and current loads in the plant, and in such cases it is often very convenient to know how to change the meters on hand, to indicate voltages or currents other than those for which they were designed. This can quite easily be done by changing the resistors on voltmeters or the shunts used with ammeters.

In recent years instrument manufacturers have begun to standardize on the construction of essential parts of meters. This not only reduces original costs and makes it easier to secure repair parts, but it also makes certain meters more flexible or adaptable to a wider range of service. For example, many volt meters and ammeters are now made with a standard moving coil having a resistance of $2\frac{1}{2}$ ohms and designed to give full scale deflection of the pointer with a current of 20 milliamperes, or .020 amperes. According to Ohm's Law formula, $I \times R = E$, or $.020\ I \times 2.5R = .050E$, or 50 milivolts drop, or pressure applied to force full scale current through this coil. A coil having $2\frac{1}{2}$ ohms for a 50 millivolt reading would be on a basis of 50 ohms per volt, as one volt or 1,000 m.v. $\div$ 50 m.v. = 20, and $20 \times 2.5 = 50$.

Now if we wish to use this 50 m. v. meter to measure 100 m.v., or double the present voltage rating, we should simply double the resistance of the meter circuit or add $2\frac{1}{2}$ ohms more resistance in series with the $2\frac{1}{2}$ ohm moving coil. Then $2\frac{1}{2} + 2\frac{1}{2} = 5$ ohms total resistance, which when connected across a 100 m.v. circuit would draw $.100 \div 5$ or .020 amperes and again give full scale deflection. If we now remark or recalibrate the scale for 100 m.v., we have doubled the range of the meter.

You can readily see that if the $2\frac{1}{2}$ ohm coil were connected on a circuit of double its rated voltage without increasing the resistance, the coil would receive double current and be burned out. Therefore, in changing voltmeter resistances to adapt the meter for correct readings of higher voltage values, we simply use the following formula to determine the correct resistors to use in series with the meter coil:

$$\frac{\text{Desired voltage range}}{\text{Full scale meter coil current}} = \text{Total resistance for meter circuit.}$$

Then by subtracting the resistance of the moving coil from this total resistance we can determine the amount of extra resistance to use in series for the higher readings. For example, suppose we wish to adapt this same meter element for a full scale reading of 150 volts, and for safe use on a 150 volt circuit.

$$\text{Then } \frac{150\ E}{.020\ I} = 7500\ R. \text{ total resistance}$$

Then $7500 - 2.5 = 7497.5$ ohms of additional resistance to be used.

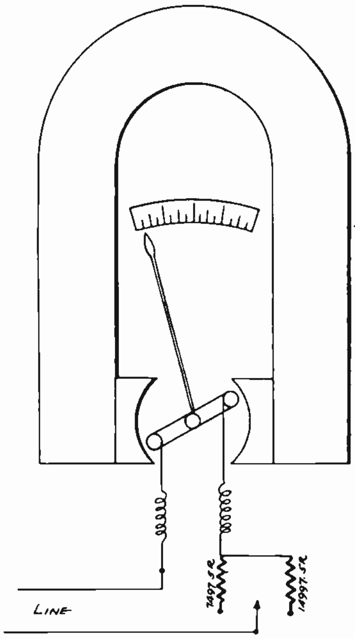

Fig. 105. This diagram shows a meter designed for reading two different voltages.

If we wish to use the same meter for dual service or 150 and 300 volt circuits, we can arrange another resistor of 14997.5 ohms as shown in Fig. 105. Then by connecting the wires of the circuits to be tested to the proper terminals or resistors we can measure either voltage. Some multiple range meters have these extra resistors located inside the case and connected to proper terminals. These meters may also have the scale marked for 3 or more voltage ranges.

The same changes can be applied to ammeters to adapt them for other ranges by changing the resistance of the shunts which are used with this same standard meter element and $2\frac{1}{2}$ ohm moving coil. Using only the meter coil without any shunt the instrument's capacity and full scale reading would be only 20 milli-amperes. If we wish to change it to measure current up to 100 M.A. or 5 times its former rating, we would place in parallel with the moving coil a shunt having a resistance one-fourth that of the coil or, $2.5 \div 4 = .625$ ohms resistance for the shunt.

With this shunt connected in parallel with the meter as shown in Fig. 106, the current will divide in inverse proportion to the resistance of the two parallel paths, and 4/5 of the current, or 80 M.A.

will pass through the shunt, while 1/5 of the current, or 20 M.A. will pass through the meter coil.

When making such changes for scale readings of 2 amperes or less, we should determine the shunt resistance according to the desired division of current between the meter coil and the shunt, as we have just done in the foregoing problem. This is due to the fact that in order to obtain readings which are accurate at least within one per cent on

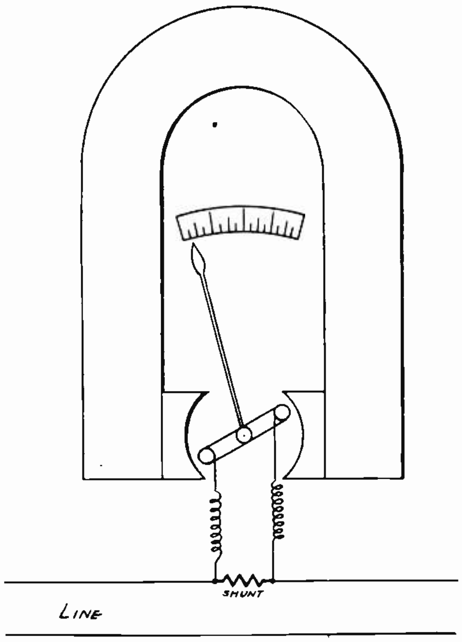

Fig. 106. This figure shows how the ammeter shunt is connected in parallel with the meter coil.

such small current loads, we must consider the amount of current which flows through the meter element. However, for changes over 2 amperes the following simple formula can be used to determine the shunt resistance:

$$\frac{\text{Voltage rating of meter coil}}{\text{Desired current capacity}} = \text{Resistance of shunt.}$$

Then if we want to change this same type of meter with the 50 millivolt coil to measure currents up to 10 amperes at full scale reading,

$$\frac{.050}{10} = .005 \text{ ohm shunt}$$

to be used in parallel with the meter element. Note that the shunt resistance is 1/500 of the meter coil resistance, and the meter coil current of .020 is 1/500 of the new full scale current of 10 amperes. If we desire to change this type of meter to read 200 amperes, then,

$$\frac{.050}{200} = .00025 \text{ ohm shunt.}$$

Meters which use these standard coils of 2½ ohms resistance for M.A. current, at 50 ohms per volt, are guaranteed by the manufacturers for accuracy within one per cent. This is accurate enough for all ordinary shop tests. When a higher degree of accuracy is required for laboratory measurements, etc., meters with higher resistance moving elements are used. The more resistance per volt which is used in the meter coil, the higher the degree of accuracy will be.

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ESTABLISHED 1899

DIRECT CURRENT POWER AND MACHINES

Section Three

D. C. Motors

Operation and Principles

Types, Series, Shunt, and Compound

Uses and Applications, H. P. and Efficiency Tests

Controllers

Manual Starters, Speed Controls, Automatic Controllers

Drum Controls, Overload Devices

Carbon Brushes

Types, Applications, Pressure, Fitting and Care

Maintenance of D. C. Machines

Trouble Charts, Testing, Tools, Repairs

DIRECT CURRENT MOTORS

An electric motor, as you have already learned, is a device for converting electrical energy into mechanical energy, or to perform just the opposite function to that of a generator. Motors supply mechanical energy to drive various machines and equipment by means of belts, gears, and direct shaft connections.

When electricity from the line is supplied to terminals of the motor, it develops mechanical force or energy which tends to rotate its armature and any equipment which may be attached to its shaft. This twisting effort or force is known as the Torque of the motor.

114. TYPES OF D. C. MOTORS

Direct current motors can be divided into three general classes, the same as D. C. generators were, **namely, Shunt, Series, and Compound motors. These** motors are classified according to their field connections with respect to the armature, in the same manner in which the generators were classified.

Compound motors can be connected either cumulative or differential. With generators we find that the shunt, series, and compound types each have different voltage characteristics. With motors, **the effect of these different field connections is to produce different speed and torque characteristics.**

Motors are made with various types of frames, known as **Open Type, Semi-enclosed, and Closed Type** frames.

Fig. 105 shows a modern D. C. motor with an open type frame. A frame of this type allows easy access to the commutator, brushes and parts, for adjustment, cleaning and repairs; and also allows good ventilation. Open type motors are generally used where they are to be operated in clean places, and where there is no danger of employees coming in contact with their live parts; and no danger of fire or explosions which might be caused by sparks at their brushes.

Fig. 105-A shows a motor with a semi-enclosed frame. Frames of this type will enclose all the live and moving parts of the motor, and at the same time allow ventilation through the small openings provided in the end plates and around the motor frame.

Fig. 106 shows a motor with a completely enclosed frame. Motors of this type are often built larger and wound with larger wire, so they do not develop as much heat. In some cases they are practically air-tight, and have ventilating tubes attached to their casings to bring cooling air from another room.

Motors with enclosed frames of this type can be used in places where the air is filled with dust and dirt, or possibly vapors or explosive gases.

Enclosed frame motors should always be used where abrasive dust or metal dust is present in the air, or in mills where wood or grain dust might be exploded by any possible sparks from brushes.

115. MOTOR SPEEDS AND H. P.

D. C. motors are always rated in horse power, and range in size from those of a small fraction of one horse power to those of several thousand horse power each. The smaller motors are used for driving household appliances, laboratory equipment, and small individual shop machines, such as drill presses, small lathes, etc. Medium-sized motors, ranging from one horse power to several hundred horse power each, are used for driving machinery in factories and industrial plants, for street railways and electrical locomotives, and for elevator machinery. The larger types, ranging from several hundred to several thousand horse power each, are used principally in steel mills and on electrically-driven ships.

The horsepower ratings of motors refer to the maximum continuous output they can deliver without overheating.

The speed at which D. C. motors are designed to operate depends principally upon their size, because the diameter of the armature, as well as the R. P. M., are what determine the centrifugal forces set up in the conductors and commutator bars.

Very small motors commonly have speeds from 2000 to 4000 R. P. M., while motors of medium or average size, ranging from 1 to 25 h. p., usually rotate at speeds from 1000 to 2000 R. P. M.

Very large motors operate at much lower speeds, generally ranging from 100 to 500 R. P. M.; although some large steel-mill motors have speeds as low as 40 R. P. M.

The speed at which any D. C. motor operates is always determined by the counter-E. M. F. which is generated in its armature.

This counter-E. M. F., or back-voltage, we might

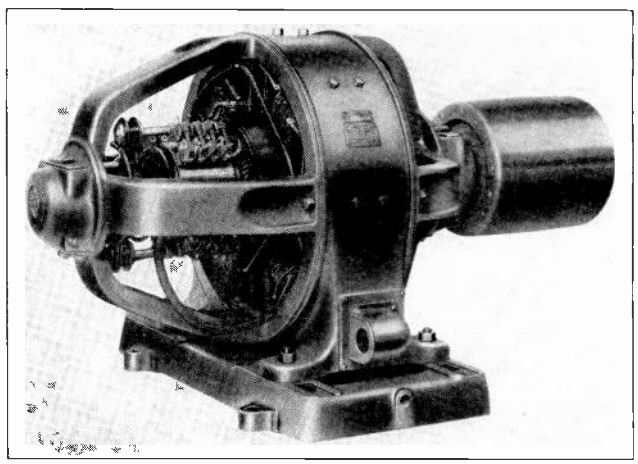

Fig. 105. This photo shows a modern D. C. motor with an open type frame. Note the easy access a frame of this construction provides to the commutator, brushes, and field coils.

say acts as a throttle to control the current flow through the armature, and therefore acts as a governor of the motor speed. In the following pages this principle will be explained more fully in connection with the characteristics of the different types of motors.

116. MOTOR SPEED REGULATION AND CONTROL

In referring to the characteristics and operation of electric motors, we frequently use the terms **Speed Regulation** and **Speed Control.** These terms have entirely separate meanings, and their difference is very important.

Speed Regulation refers to changes in speed which are automatically made by the motor itself, as the load on the machine is varied. Speed regulation is largely determined by the construction of the motor and its windings and is a very important factor in the selection of motors for different classes of work.

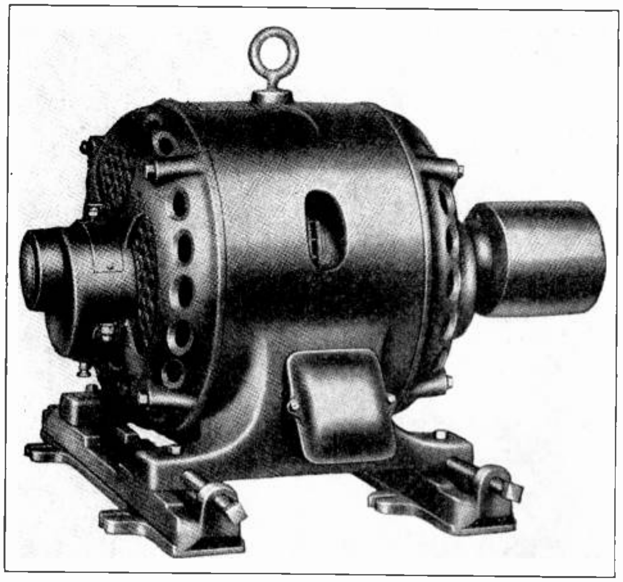

Fig. 105-A. This motor has a frame of the semi-enclosed type. The openings at the ends and around the frame are provided for air circulation and cooling.

The speed regulation of a motor is usually expressed in percentage and refers to the difference in the speed of the machine at no load and full load. It can be determined by the following formula:

$$\text{Speed regulation} = \frac{\text{No load R. P. M.} - \text{full load R. P. M.}}{\text{No load R. P. M.}}$$

For example, if we have a motor that operates at 1800 R. P. M. when no load is connected to it and slows down to 1720 R. P. M. when it is fully loaded, its speed regulation would be:

$$\frac{1800 - 1720}{1800}, \text{ or } .044 +$$

This would be expressed as 4.4%.

Motor speed regulation is entirely automatic and is performed by the motor itself, as the load varies.

The term **Speed Control** refers to changes which are made in the motor speed by the use of manual or automatic control devices. These speed control devices are usually external to the motor and consist of some form of variable resistance. They will be fully explained in the following pages.

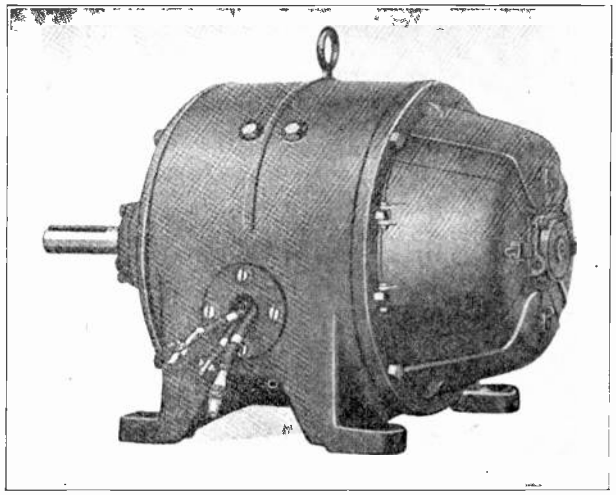

Fig. 106. The above motor has a frame of the enclosed type. Motors of this type are particularly well suited for operation in places where the air is full of dust or vapor.

117. MOTOR RATINGS IN VOLTS, AMPERES, AND H. P.

The rating of a D. C. motor in horse power, amperes, and volts depends on the same factors in their design as the rating of generators does. The motor ratings in horse power are also based on the same factor of the temperature increase in their windings when operated at full rated load.

For example, a 10 h. p. motor is one that when supplied with the proper voltage for which it is designed will drive a 10 h. p. mechanical load continuously without overheating its windings. The current required by a motor is, of course, proportional to the mechanical load in h. p. which it is driving.

In addition to carrying the load without heating the windings, the motor must also be able to carry its full load current without excessive heating or sparking at the brushes and commutator.

Motors are generally designed to carry overloads of a greater amount and for longer periods of time than generators are. Most D. C. motors can carry a 25% overload for a period of two hours, without serious overheating.

We have already learned that D. C. motors are similar to D. C. generators in all details of their mechanical construction. In fact, manufacturers frequently use the same D. C. machines either as motors or generators, by merely changing the name plates on them and making a few minor changes in the connections of the field windings and setting of the brushes.

118. MOTOR PRINCIPLES

Electric motors develop their torque or turning effort by reaction between the flux around the armature conductors and the flux of the field poles, as has been previously explained. When the magnetic lines of force from the field poles attempt to pass through the armature core and windings, they collide with the revolving flux around the armature conductors, as shown in Fig. 107.

Where the lines of force passing from the N. to S. field poles collide with lines of armature flux in the opposite direction, they will, of course, tend to unite and travel in the same direction. This causes the majority of the magnetic lines leaving the N. pole in Fig. 107 to swing upward over the positive conductor, creating a very dense magnetic field above it and a weaker field below it. As the field lines go on across the armature and collide with the downward lines on the left side of the negative armature conductor, the majority of the lines will again join with this revolving flux and pass on the under side of this conductor.

As we know that magnetic lines of force always tend to shorten themselves, or take the most direct path possible through any external circuit, it is evident that this distortion of the field flux and the crowding of the lines above the positive conductor and under the negative conductor will tend to revolve the conductors in a counter-clockwise direction. From the illustration in Fig. 107, we can see that the torque of a D. C. motor is obtained largely from the reaction between the magnetic lines of force of the armature and field flux. There is also the force of attraction and repulsion between the field poles and the poles which are set up on the surface of the armature. That is why D. C. motors are often said to operate on the "repulsion" principle.

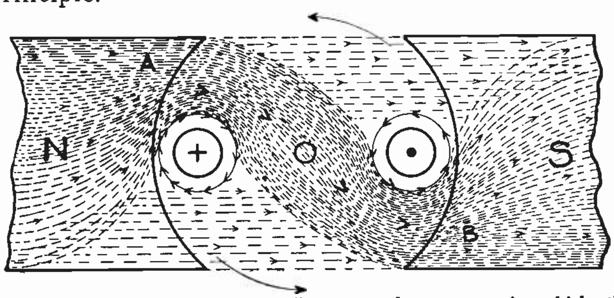

Fig. 107. The above diagram illustrates the manner in which the reaction between the lines of force from the armature and field windings set up the torque or turning effort in a motor.

119. MOTOR TORQUE, SPEED AND H. P.

The torque exerted by such a motor will, of course, depend on the strength of the magnetic flux from the field poles and the strength of the armature flux. Therefore, the torque exerted by a motor can be increased by increasing either the field strength or the armature current, or both.

The horse power or mechanical power output of a D. C. motor is proportional to the product of its torque and speed. The higher the speed at which a motor is operated while maintaining the same amount of torque, the greater will be its horse power.

D. C. motors rated at higher speeds will produce the same horse power with smaller frames and armatures. The cost of high speed motors is therefore much less per h. p. A motor frame that is rated at 5 h. p. at 900 R. P. M. will deliver **10 h.** p. at 1800 R. P. M.

120. DIRECTION OF MOTOR ROTATION

The direction of rotation of a D. C. motor can be easily determined by the use of Fleming's left-hand rule. This rule is similar to the right-hand rule which we have learned to use for generators.

Hold the first finger, thumb, and remaining fingers of the left hand all at right angles to each other. Let the first finger point in the direction of flux from the field poles, the remaining fingers in the direction of current through the armature conductors, and the thumb will then indicate the direction of rotation of the armature.

This rule can be quickly and easily applied to diagrams such as shown in Fig. 107 and can also be used on the actual machines, when the armature conductors and connections to the commutator can be seen and the polarity of the field poles is known.

The direction of rotation can also be easily determined with diagrams such as shown in Fig. 107, by simply remembering that the repelling or crowding force on the armature conductor will be on the side where its flux lines join with those of the field flux.

From this study of the direction of **rotation of** motors, you can see that any D. C. motor can be reversed either by reversing the direction of current through the armature winding or by reversing the field connections to change the polarity of the field poles. Refer to Fig. 107, and using the left-hand rule, note the direction in which these conductors would rotate if their current were reversed or the poles of the motor were reversed.

121. COUNTER E. M. F. IN MOTORS

You have already learned that a voltage will be induced or generated in the armature conductors of a motor whenever the machine is running, and that this voltage is called **Counter E. M. F.** As the armature of the motor rotates, its conductors will be going through the field flux and so will produce counter-voltage in the same direction as that of the voltage of a generator rotated in the same direction as the motor. Therefore, this **counter E. M. F. induced in a motor is always in a direction opposing the applied line voltage,** but of course is normally not quite as great as the applied voltage.

The amount of counter-voltage which will be generated depends upon the number of conductors in the armature, the strength of the motor field, and the speed at which the machine is operated.

Keep this rule well in mind, because the effects of counter-voltage are extremely important in the operation of D. C. motors and control equipment.

In Fig. 108, the direction of the current and voltage applied to the armature conductors from the line is shown by the solid black symbols in the two armature conductors, and the direction of the counter-voltage generated in these conductors **with** the polarity and rotation shown, is indicated **by the** lighter symbols above the conductors.

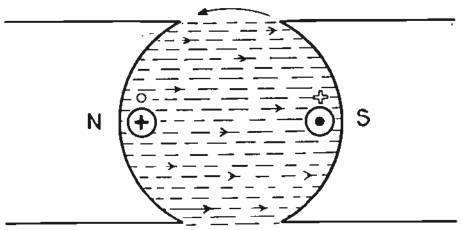

Fig. 108. The above sketch illustrates the manner in which the counter-voltage is generated in the opposite direction to the applied voltage in a motor armature.

As the counter-voltage is generated in the opposite direction to the applied line voltage, we can readily see how it limits or regulates the current which will flow through the armature and thereby acts as a governor of the motor speed.

The voltage applied to a D. C. motor armature is equal to the voltage drop in the winding plus the C. E. M. F., or

$$Ex = Ra\ Ia + CEa$$

in which

Ex = Applied voltage
Ra = Resistance of armature
Ia = Current in armature
CEa = Counter voltage of armature

Then, for example, the applied voltage of a certain 110-volt motor might be used as follows:

	Ex.		Ra Ia		CEa
No load:	110	=	1	+	109
Full load:	110	=	5	+	105

122. ARMATURE RESISTANCE NECESSARY WHEN STARTING D. C. MOTORS

When the motor armature is idle or at rest no counter-voltage is produced, and the current which would then flow through the armature would be determined entirely by its resistance and the voltage applied; according to the formula:

$$I = E \div R.$$

The resistance of D. C. motor armatures is very low, usually less than one ohm. Therefore, excessive currents would flow through them if we were to apply the full line voltage to start the machine.

For this reason, when starting D. C. motors of any but the very smallest sizes, **it is necessary to place some resistance in series with the armature to limit the current until the machine comes up to speed.** As the motor increases its speed the counter-voltage becomes higher and higher, until it limits the current to such an extent that the motor speed cannot further increase. At this point the difference between the counter-voltage and the line-voltage may be only a few volts, even on motors of quite high voltage.

The voltage effective in forcing current through the armature of a motor when it is running will be just that amount of the line voltage which is not neutralized by counter-voltage. In other words, the effective voltage will be line voltage minus counter-voltage. This is illustrated in Fig. 109, which shows the amount of the applied voltage which is neutralized by the counter-voltage developed in the armature. For this illustration we have used even and convenient figures, but in actual operation of a motor running without load the counter-voltage would be even greater in comparison to the line voltage.

If we assume the resistance of the armature in this figure to be .2 of an ohm, the current which would flow through its winding if full line voltage were applied would be 100 ÷ .2, or 500 amperes. That is, of course, provided that no external resistance were used in series with the armature.

If this same armature develops 90 volts counter-E. M. F. when rotating at full speed and under full load, the effective voltage is then only 10 volts. So, when running at this speed, the armature current would be 10 ÷ .2, or 50 amperes. From this example you can see what a great effect counter-voltage has upon the current flow in a motor armature.

123. EFFECT OF COUNTER-VOLTAGE ON MOTOR SPEED

The current required to operate a D. C. motor when no load is connected to it is comparatively small. Let us say that the armature shown in Fig. 107 requires 50 amperes to operate it at full load, and only 5 amperes to operate it when the load is disconnected. As the resistance of the armature is only .2 of an ohm, the applied voltage to run the machine at full speed and at no load would be .2 × 5, or 1 volt. So the counter-E. M. F. during the time this motor is running idle should be 100 — 1, or 99 volts.

When the mechanical load is removed from a motor, its armature immediately tends to speed up; but as the speed increases it also increases the counter-E. M. F., thereby reducing the current flow from the line and holding the motor at a constant speed slightly higher than when operated under full load. This again serves to illustrate the manner in which counter-E. M. F. governs the speed of a D. C. motor.

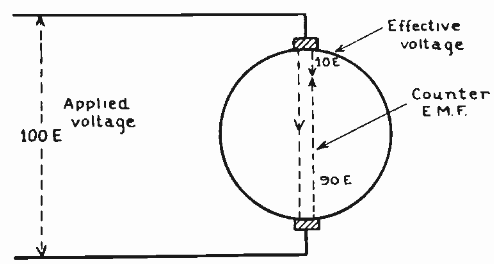

Fig. 109. From the above illustration you will note that the counter-voltage is often nearly as high as the applied voltage. This sketch illustrates the extent to which counter-voltage regulates or limits the flow through a motor armature.

124. D. C. MOTOR CHARACTERISTICS

In selecting D. C. motors for any particular work or application we must, of course, use a machine of the proper horse-power rating to start and carry the load the motor is intended to drive. In addition to the **Horse Power Rating** of the motor, the other essential points to be considered are its **Starting Torque** and **Speed Regulation** characteristics. These characteristics vary widely for shunt, series, and compound motors, which will be thoroughly explained in the following paragraphs. Make a careful study of this section because it may often be of great advantage to you on a job to be able to select the proper motors for different applications.

125. SHUNT MOTORS

The field winding of a shunt motor is connected directly across the line or source of current supply, in parallel with its armature. This shunt field winding is made up of many turns of small wire and has sufficient ohmic resistance to limit the current through the coils to the safe carrying capacity of the conductors they are wound with. As the resistance of the shunt field winding is practically constant, this current and the strength of the field it sets up will be determined by the line voltage which is applied to the motor.

A simple diagram of the connections of the armature and field of a two-pole shunt motor is shown in Fig. 110.

126. STARTING TORQUE OF SHUNT MOTORS

The starting torque of shunt motors is only fair and they cannot start very heavy loads because their field strength remains approximately constant as long as the applied voltage is constant.

While a motor is starting the armature flux is very dense, because of the heavier currents flowing through the armature at this time.

This increased armature flux of course increases the motor torque, but it also weakens the field by distorting it and forcing it to take a path of higher reluctance; so shunt motors cannot build up as good starting torque as series or compound machines do.

As the torque of the motor depends upon its field strength as well as upon the armature current, we can see that the starting torque of a shunt motor will not be very good.

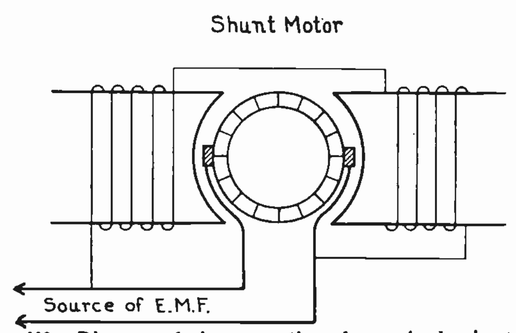

Fig. 110. Diagram of the connections for a simple shunt motor.

127. STALLING TORQUE OF SHUNT MOTORS

If a shunt motor is overloaded to too great an extent it will slow down and possibly be stopped entirely if the overload is great enough. **A motor should never be allowed to remain connected to the line when in this stalled condition, or its windings will be burned out.** This is due to the fact that when the armature is stopped it is generating no counter-voltage, and the applied line voltage will send a severe overload of current through the low resistance armature. Fuses or circuit breakers should be provided to open the line circuit to the motor in a case of this kind.

The ability of a motor to carry overload without stalling is often referred to as the **Stalling Torque** of the motor.

Shunt motors will carry their full, rated load but should not be overloaded to any great extent, as their stalling torque is not very high.

128. SPEED REGULATION OF SHUNT MOTORS

The speed regulation of shunt motors is excellent, as the strength of their field remains practically constant, and as long as the proper line voltage is applied they will maintain practically constant speed under wide variations of the load.

The shunt motor will of course slow down a little when the load is increased; but, as soon as the armature speed is reduced even slightly, this reduces the counter-voltage generated and immediately allows more current to flow through the armature, thereby increasing the torque and maintaining approximately the same speed.

The speed of shunt motors ordinarily should not vary more than three to five per cent. from no load to full load. Fig. 111 shows a set of curves which illustrate the speed regulation of series, shunt, and compound motors. Note that the speed of the shunt motor only falls off very gradually as the load is increased.

129. SPEED CONTROL AND APPLICATIONS OF SHUNT MOTORS

The speed of shunt motors can easily be varied or controlled by inserting a rheostat in series with their field. If the field is weakened, the motor speed will increase, because the reducd counter-voltage allows more current to flow through the armature.

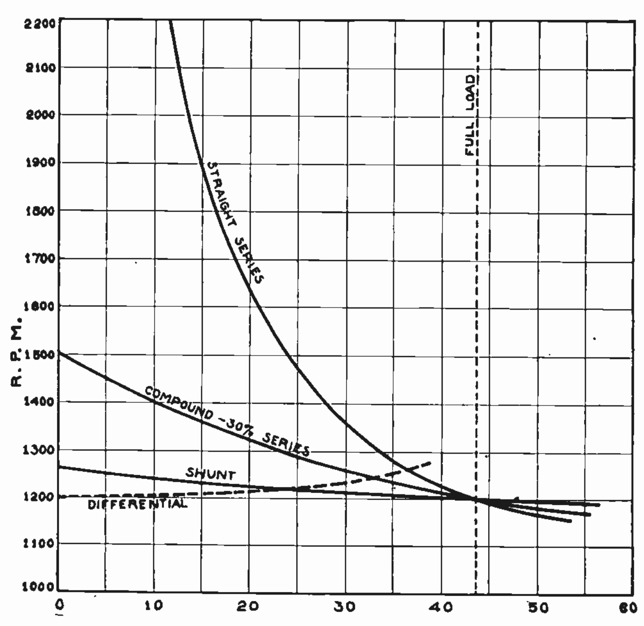

Fig. 111. The above diagram shows the characteristic speed curves for several types of D. C. motors. Note carefully the manner in which the speed varies with increase of load.

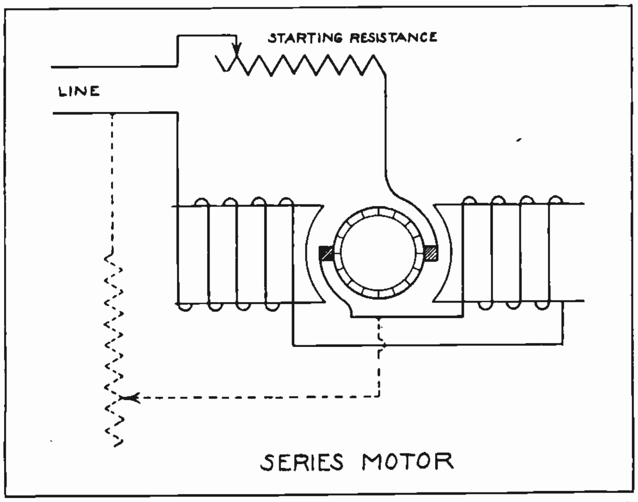

Fig. 112. Diagram of the connections for a simple series motor. The dotted lines show where a shunt can be connected in parallel with the field coils for varying the speed.

If the field is strengthened, the motor speed will decrease, because this stronger field allows the normal counter-voltage to be generated at lower speed.

The uses and applications of shunt motors are many and varied. They may be used on any job where more than full-load torque is not required for starting and where practically constant speed is essential. They are extensively used for pumps, elevators, motor-generator sets, and for the operation of lathes and various machines used in manufacturing appliances.

130. SERIES MOTORS

Series motors have their field coils connected in series with the armature and the line, as shown in Fig. 112. The windings for the fields of series motors are made of heavy copper wire or strap copper, and may consist of anywhere from a few dozen to a few hundred turns.

The strength of the field of the series motor depends upon the amount of current flowing through the armature and series field coils.

As the armature current depends upon the motor load and speed, the field strength of a series motor will be much greater at heavy loads and low speeds than at light loads and higher speeds, when the armature is developing a greater counter-E. M. F.

131. STARTING TORQUE

The armature current is usually at its greatest value when starting a motor because when the armature is idle or rotating at low speeds it doesn't generate much counter-E. M. F., and very heavy currents will flow through the armature until it comes up to speed. For this reason the starting torque of series motors is excellent.

The torque of motors of this type varies directly with the square of the armature current, because any increase of current through the armature also increases the field strength, as the two windings are in series.

Series motors are capable of starting very heavy loads, and this makes them particularly adaptable for use on street cars and electric railways, and other special applications where the machinery to be driven is difficult to start.

132. STALLING TORQUE

Series motors also have excellent stalling torque, because, when they are overloaded, their speed is reduced and less counter-voltage will be generated in the armature. This allows more current to flow both through the armature and field coils, greatly increasing the flux around the armature conductors and from the field poles.

It is almost impossible to stall a series motor with any reasonable load, because the slower the speed becomes, the more current will flow through the armature and field of the motor, and the greater its torque becomes.

Of course, it is possible to burn out a series motor by overloading it in this manner, if the overload is left on it too long.

133. SPEED REGULATION

The speed regulation of series motors is very poor, because their speed varies inversely with the load applied. Any increase of load actually strengthens the field flux of the series motor. This causes a higher counter-voltage to be generated and momentarily reduces the armature current, until the speed of the motor drops enough lower to bring the counter-voltage back to normal or less than normal, to allow the increased current flow required for the additional load.

If some of the load is removed from the series motor, this decreases the flow of current and weakens its field. The weaker field develops less counter-voltage and momentarily allows more current to flow, until the speed is increased enough to build the counter-voltage up again somewhat above normal value.

Thus, series motors will operate at very high speeds when the load is light and they will overspeed if the load is entirely disconnected. For this reason **series motors should never be operated without load,** or the speed will increase to a point where centrifugal force may throw the armature apart.

Series motors should always be attached to their load by gears or direct shaft connection, and **never** by belts. If a series motor were belted to its load and the belt should break or slip off the pulleys, the motor might dangerously overspeed before it could be stopped.

In Fig. 111, the speed curve for a series motor is shown, and you will note how rapidly the speed decreases with any increase of load.

There are certain applications for motors, however, where the decrease of speed with increase of load is very desirable.

134. SPEED CONTROL

The speed of a series motor can be controlled or varied at will by the use of resistance in series with the motor. Increasing this resistance will reduce the voltage applied to the armature and series field, thereby momentarily reducing the current flow and the torque, until the motor reduces its speed and counter-E. M. F. to a point where the counter-E. M. F. and the effective voltage again balance the reduced applied voltage.

This is one of the methods used to vary the speed of electric street cars, by cutting resistance in or out of the motor circuit with the drum controller. When the resistance in series with the machine is varied, the voltage across the armature is varied accordingly, and the armature slows down or speeds up correspondingly until the counter-E. M. F. and effective voltage again equal the applied voltage.

The speed of series motors can also be varied by connecting a shunt in parallel with their field coils, as shown by the dotted lines in Fig. 112. This shunt merely passes a certain amount of the armature current around the field winding, and thereby weakens the field strength and increases the speed of the motor. These shunts can not be used to decrease the motor speed below normal.

135. USES AND APPLICATIONS OF SERIES MOTORS

The uses and applications of series motors are somewhat limited because of their wide variation in speed when the load is varied, and their tendency to overspeed when the load is removed. Series motors are not adapted to driving machinery or equipment which place a variable load on the motor and require practically constant speed.

Series motors are used principally for electric cranes, hoists, and railway service, and are well suited to this work because of their high torque at low speeds and low torque at high speeds. They are particularly well adapted to electrical traction work because of their splendid starting torque, which enables them to start heavy cars quickly and also climb hills with heavy loads. Their speed characteristic is also an advantage in this case, because it is possible to obtain high speeds with cars operated by this type of motor when the cars are running on the level or with light loads.

136. COMPOUND MOTORS

Compound D. C. motors have some of the characteristics of both the shunt and series motors, as they have both a shunt and series field winding on each pole. The shunt field of the ordinary machine is made up of many turns of small wire and is connected in parallel with the armature and line, as shown in Fig. 113. The strength of the shunt field flux will therefore be proportional to the applied line voltage and will be practically constant as long as this voltage is not varied.

The series field winding is usually made of very heavy copper wires or strap copper and may vary from a few turns to 100 turns or more per pole. This winding is connected in series with the armature, as shown in Fig. 113, and carries the full load current which passes through the armature.

The strength of the series field will therefore be proportional to the load applied to the motor. **The shunt field, however, is the one that always determines the polarity of the machine under ordinary conditions** and, therefore, it is called the main field winding.

Compound motors can be connected either cumulative or differential, by simply reversing the connections of their series field windings. The connections shown in Fig. 113 are for a cumulative compound motor, and most D. C. motors are understood to be connected in this manner, unless they are marked or designated as differential-compound.

With the series field connected for cumulative-compound operation, the current flows through these coils in the same direction that it does through the shunt coils, and therefore aids in setting up a stronger field when there is any load on the motor.

137. STARTING AND STALLING TORQUE

Cumulative-compound motors have a very much better starting-torque than shunt motors, because the heavier armature currents which flow during starting also pass through the series field and greatly strengthen its flux, thereby increasing the motor torque.

Motors of this type can be used for starting very heavy loads or machinery that is difficult to start and bring up to speed.

The stalling torque of cumulative-compound motors is also quite high, because any increase of load on the machine will increase its armature current and the current through the series field. This increases the flux of the field poles, which in turn increases the motor torque and enables it to carry the additional load at slightly reduced speed.

Such motors can be allowed to carry reasonable overloads of 15 to 25 per cent. as long as they don't overheat enough to damage their insulation.

138. SPEED REGULATION AND APPLICATIONS

The speed regulation of cumulative-compound motors can be considered as fair. Their speed will vary inversely with the load, because any increase of load also increases the field flux due to the action of the series winding; and when the field flux is increased, the armature speed must decrease, in order

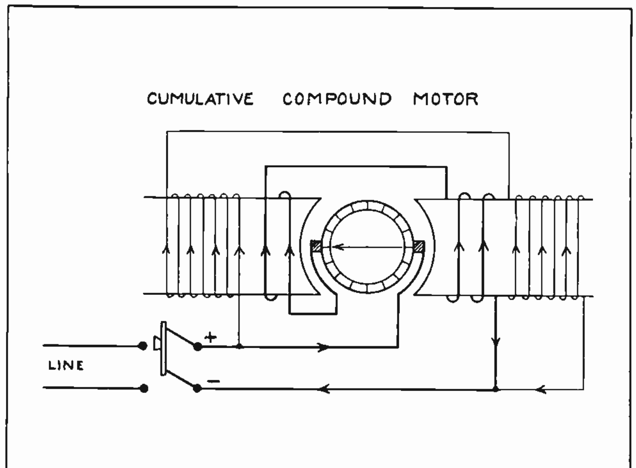

Fig. 113. Diagram of connections for a cumulative compound motor. Note that the series field winding is connected so it will aid the shunt field winding in providing a strong field.

to lower the counter-E. M. F. sufficiently to allow enough current to flow to carry the load. The stronger the field of any motor, the lower will be the speed at which it can generate the normal counter-E. M. F.

Compound motors are used extensively to drive power shears, the rolls of steel mills, and in factories and industrial plants for running machines which require good starting and stalling torque and don't require very close speed regulation.

139. DIFFERENTIAL COMPOUND MOTORS

When compound motors are connected for differential operation their characteristics change considerably from those of cumulative machines.

A differential compound motor has its series field so connected that the current will flow through it in the opposite direction to that of the current in the shunt field windings, as shown in Fig. 114. This tends to weaken the field flux whenever any load is being carried by the motor.

The shunt field winding is the main winding and under ordinary conditions it determines the polarity of the field poles. Occasionally, however, when these motors are started up rather suddenly and under heavy load, the current flow through the differential series winding becomes very strong; and due to its strong flux and the inductive effect which it has on the shunt field coils during the time this flux is building up around the series winding, it may overcome the shunt field flux and reverse the polarity of the field poles. This will cause the motor to start up in the wrong direction.

To avoid this, the series field of a differential motor should be short-circuited when starting. This can be done by the use of a single-pole knife switch of the proper size, connected across the series field terminals, as shown in Fig. 114.

140. STARTING TORQUE AND STALLING TORQUE

The starting torque of an ordinary differential-compound motor is very poor, even poorer than that of a shunt motor. This is due to the effect of the heavy starting currents flowing through this field and weakening the flux of the shunt field to such an extent that the motor has very poor starting torque. Motors of this type are usually started without any load connected to them.

A reversing switch can be used to reverse the polarity of the differential field and make the motor operate cumulative during starting, and thereby improve the starting torque of this motor.

Differential motors will not carry overload without stalling. In fact they will usually only carry about 75% of the full rated load of a shunt motor of the same size. Whenever the load on such a machine is increased, the series field current is increased and, because it flows in the opposite direction of that in the shunt winding, it tends to neutralize and weaken the total field flux and also weaken the load-pulling torque.

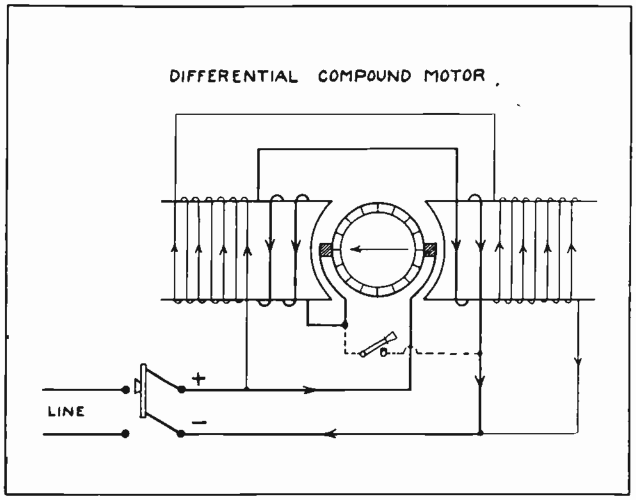

Fig. 114. Differential compound motor connections. Note that the series field is connected so it will oppose and weaken the effect of the shunt field.

141. SPEED REGULATION AND APPLICATIONS

Differential-compound motors have excellent speed regulation up to a certain amount of load. As the load is slightly increased, the motor tends to slow down, but the increased current through the differential series field immediately weakens the shunt field flux and thereby causes the counter-E. M. F. in the armature to be reduced.

This allows more current flow through the armature and maintains the speed at normal value. With just the proper number of turns on a differential series field, the tendency of the motor to slow down with increased load and the tendency to speed up with weakened field can be so balanced that they will neutralize each other, and the speed will remain almost perfectly constant if the load change is not too great.

Note the speed curve shown for this type of motor in Fig. 111.

Differential-compound motors are not used very extensively, because of their very poor starting torque; but they have certain applications where very little starting torque is required and good speed regulation is essential. The operation of textile mill machinery is a good example of this application.

A convenient, practical method for determining whether a compound motor has its series field connected differential or cumulative is to operate the motor and note its speed. Then reverse the series field connection and again note the speed. Whichever connection gives the most speed is the differential connection of the series field winding.

142. BRAKE HORSE-POWER TEST FOR MOTORS

Occasionally it may be desirable to make an actual test of the horse-power output of a motor, in order to determine its condition or efficiency. This can be done by arranging a brake or clamp to apply load to the pulley of the motor and thereby measure the pull in pounds or the torque exerted by the motor.

This method is known as the Prony Brake Test.

Fig. 115 shows the equipment and method of its use for making this test. The brake can be made of wood blocks cut to shape to fit the pulley and fitted with bolts and wing nuts so the grip or tension of the blocks on the pulley can be adjusted. When making a number of these tests, it is also a good plan to line the curved faces of the block with ordinary brake lining such as used on automobiles. This makes it possible to apply a smoother braking effect without generating too much heat due to the friction.

An arm or bar, of either wood or metal, can be attached to the brake blocks as shown in the figure, and fitted with a bolt or screw eyes for attaching the scales to the end of the bar. A spring scale, such as shown in Fig. 115, can be used, or the bolt on the underside of the arm end can be allowed to rest on the top of a platform scale.

The brake arm should preferably be of some even length, such as 2 ft. or 3 ft., in order to simplify the horse-power calculation. The arm length is measured from the center of the shaft to the point at which the scale is attached.

With a device of this kind, load can be gradually applied to the motor by tightening the brake shoes or clamps until the motor is fully loaded.

An ammeter can be used in series with one of the line leads to the motor to determine when the machine has been loaded to its rated current capacity. In case an ammeter is used, a voltmeter should also be used, to see that the proper line voltage is applied to the motor at the time of the test. A wattmeter can be used instead of the voltmeter and ammeter if desired.

When the brake has been adjusted so that the motor is drawing its full rated load in watts, the pound pull on the scale should be noted and the speed of the motor in revolutions per minute should be carefully checked.

The adjustment on the brake should be maintained to keep the motor pulling the same amount on the scales and drawing the same load in watts during the time the speed is being checked.

The motor speed can easily be checked by means of a speed counter or tachometer applied to the end of its shaft while running. A watch with a second-hand should be used for gauging the time accurately.

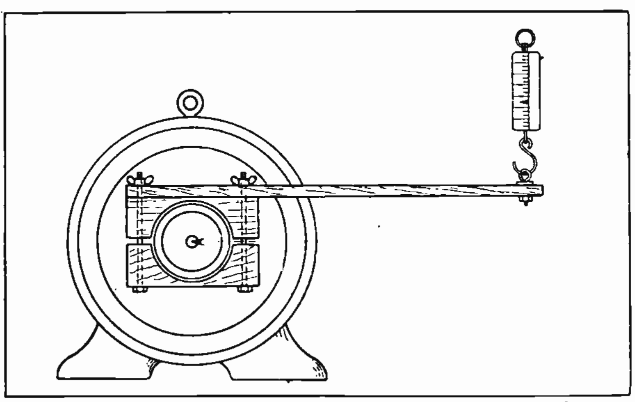

Fig. 115. The above diagram illustrates the method of making a brake-h. p. test on a motor.

143. HORSE POWER CALCULATION

The horse power of a motor is proportional to the product of its torque and speed. Therefore, when we know the length of the lever arm in feet, the pull in lbs. on the scales, and the speed of the motor in R. P. M., we can easily determine the horse-power output by the following simple formula:

$$\text{h. p.} = \frac{2 \times \pi \times \text{R. P. M.} \times \text{P} \times \text{L}}{33{,}000}$$

In which:

h. p. = the horse power developed by the motor

π = 3.1416, or the ratio between the diameter and circumference of a circle. ($2 \times \pi = 6.28$)

R. P. M. = Speed of the motor in revolutions per minute

P = Lbs. pull on the scale

L = Length of lever arm in feet

33,000 = Number of foot-pounds required per per minute for one h. p.

As an example, suppose we have made a test on a motor using a brake arm two ft. in length, and have found that when the motor is fully loaded according to the electrical instruments, it applies 9 lbs. pull on the end of the arm and revolves at a speed of 1500 R. P. M. Then, according to our formula:

$$\text{h. p.} = \frac{6.28 \times 1500 \times 9 \times 2}{33{,}000} \text{ or } 5.1 \text{ h. p.}$$

144. EFFICIENCY TESTS

The efficiency of a motor is, of course, an important item, especially where a large number of motors are being chosen for continuous operation of certain equipment. The higher the efficiency of any motor, the greater the h. p. it will produce from a given amount of electrical energy in watts, and the less power will be wasted in losses within the machine.

These losses are partly mechanical, such as bearing friction and "windage" due to the armature revolving through the air at high speed. They are also partly electrical, such as losses in the armature and field windings due to resistance and to a certain amount of energy being transformed into heat, and the slight magnetic losses due to hysteresis and eddy currents.

The efficiency of D. C. motors may vary from 50% or less for the very small fractional horse power machines up to 90% for the larger ones, and even higher than this for extremely large motors.

The efficiency of ordinary motors from 5 to 50 h. p. will usually range between 75 and 90 per cent; so, when the efficiency of a machine is not known, a good average figure to use is 80% or 85%.

As a general rule, the larger the motor, the higher will be its efficiency. Fig. 116 shows a table in which are given the efficiencies of several sizes of

EFFICENCY OF 230 VOLT COMPOUND D.C. MOTORS			
SIZE IN H.P.	AT ½ LOAD	AT ¾ LOAD	AT FULL LOAD
5	73 %	78 %	80 %
10	79 %	82.5 %	85 %
25	84 %	87 %	87.5 %
50	85 %	87.5 %	88.5 %
200	87 %	89 %	91.5 %

Fig. 116. This table gives the approximate efficiencies of various sized D. C. motors at various percentages of load.

motors, from 5 to 200 h. p. You will also note by examining this table that the efficiency of any motor is better at full or nearly full load. Therefore, it does not pay to operate motors lightly loaded whenever it can be avoided by the selection and use of motors of the proper size. In many cases, motors which are larger than necessary have been installed to operate certain machines, because these machines require considerable starting torque. In a case of this kind, the selection of a different type motor with a better starting torque can often effect considerable power saving.

145. EFFICIENCY CALCULATION

The efficiency of any motor can be found by dividing its output in watts by the input in watts. This is stated by the following formula:

$$e = \frac{W\ O}{W\ I}$$

In which:

e = the efficiency of the motor in per cent.
W O = watts output
W I = watts input

The output and input can both be determined in horse power or kilowatts, if preferred, and used in the same manner in the formula.

When we have made a test of the horse power of a motor by the Prony brake method and have measured the electrical power input either with a wattmeter or a voltmeter and ammeter, it is then an easy matter to determine the efficiency of the machine with the formula just given.

For example, suppose we have tested a machine and found its full load output to be 35.5 h. p. During this test the wattmeter connected to the motor leads indicated that it was consuming 31,150 watts. To obtain the output in watts, we multiply 35.5 by 746, as there are 746 watts in each h. p., and we find that the output is 26,483 watts.

Then, according to the formula, the efficiency of this motor will be found as follows:

$$e = \frac{26{,}483}{31{,}150}, \text{ or } 85+\ \%\ \text{efficiency}$$

Fig. 117-A shows the method of conecting a wattmeter to the terminals of a motor for determining the input or energy consumed. At "B" in this same figure are shown the proper connections for a voltmeter and ammeter used to determine the input of the motor.

The readings of the voltmeter and ammeter can be multiplied to obtain the power input in watts.

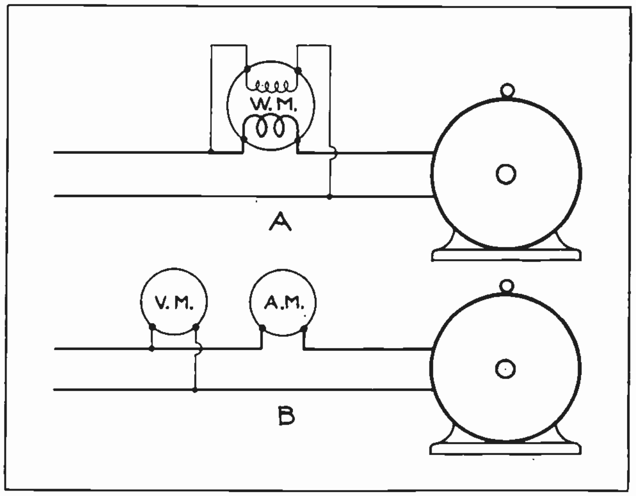

Fig. 117. The above diagram shows the method of connecting a wattmeter or voltmeter and ammeter, to determine the KW or h. p. input to a motor.

D. C. MOTOR STARTERS AND CONTROLS

There are two general types of D. C. motor control equipment. One of these is used for starting duty only, and the other can be used both for starting and for controlling or regulating the speed of the motors while running.

Motors of ¼ h. p. or less can be started by connecting them directly across the line, as their armatures are so small and light in weight that they come up to full speed almost instantly. Therefore, the heavy rush of starting current does not last long enough to overheat their windings.

Medium-sized and larger D. C. motors should never be connected directly across the full line voltage to start them, as their heavier armatures require more time to speed up and develop the necessary counter-voltage to protect them from excessive starting current.

If these armatures are connected directly across full line voltage when they are at rest, the rush of starting current through them is likely to be more than 10 times full-load current. This excessive current will overheat the winding, and also possibly damage the insulation of the coils by the powerful magnetic field it sets up and the mechanical forces the coils exert on the slots in trying to practically jerk the armature up to full speed.

So, for this reason, a starting resistance should always be connected in series with the armature of a D. C. motor when starting it, and left in the circuit until the motor armature has reached full speed and has built up its own protective counter-voltage.

When the current flows through this resistance, it causes sufficient voltage drop so that only about one-fourth of the line voltage is applied to the armature. Fig. 118 shows the method of connecting the starting resistance in series with the motor armature.

These starting resistances are usually arranged so they can be gradually cut out of the armature circuit as the motor comes up to speed, and when full speed is reached the resistance is all cut out.

The starting current for D. C. motors should be limited to about 1½ to 2½ times full-load current. It is therefore necesary that starting rheostats have the proper resistance value and current capacity for the motors with which they are usd.

146. TIME ALLOWED FOR STARTING MOTORS

The period of time for which the starter resistance should be left in series with the motor when starting, depends upon the size of the motor and the nature of the load attached to it. A motor connected

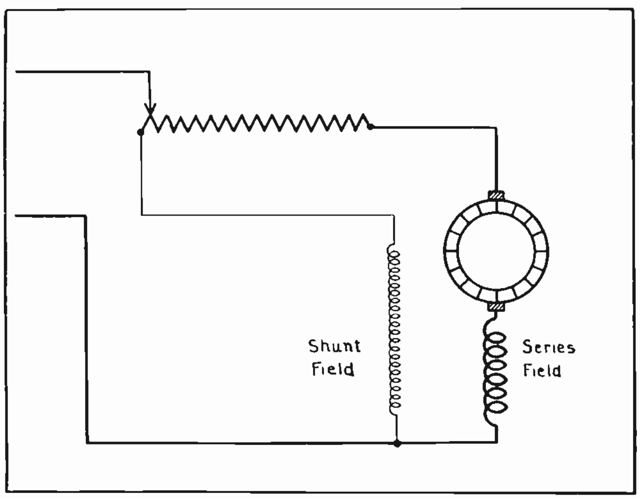

Fig. 118. This simple sketch shows the manner in which a resistance is used in series with the armature when starting a D. C. motor.

to a heavy load, of course, requires more time to come up to full speed, and the larger the armature of a motor, the more time is required for it to reach full speed.

Usually from 15 to 30 seconds will be required on ordinary motors. This rule, however, cannot be strictly followed, as the time allowed for starting a motor must be largely a matter of observation and good judgment on the part of the operator. One can readily tell by the sound of the motor when it has reached full speed.

While starting and operating various motors you will gain considerable practice in judging the time required for different motors. Always watch and listen to the motor closely when starting it up, and never leave the resistance in the circuit any longer than necessary, or it is likely to become damaged by overheating.

147. MOTOR STARTING RHEOSTATS

Starting resistances or **Rheostats,** as they are called, should never be used to regulate the speed of a motor after it is running. Starting rheostats are designed to carry the armature current only for a very short period and should then be cut out of the circuit. If they are used for speed regulation and left in the circuit for longer periods, they are very likely to become overheated to a point where the resistance metal will burn in two and result in an open circuit in the rheostat.

Armature starting resistances for small machines are usually made up of iron wire, or wire consisting of an alloy of nickle and iron. This resistance wire is wound on an insulating base, or form of asbestos or slate. The turns of the coil are so spaced that they don't short together.

The taps are made at various points along the coil and are connected to segments or stationary contacts which are mounted on the face-plate of the starter. A lever arm with a sliding contact is then used to cut out the resistance gradually as the motor comes up to speed. See Figs. 121 and 123.

148. SPEED CONTROL RHEOSTATS

Speed-regulating resistance can be used for starting motors and also for controlling their speed over indefinite periods. Rheostats for this use are made of larger and longer resistance material and are designed to carry the armature current for long periods without damage from overheating.

Speed-regulating resistances are in some cases made of heavy iron wire, but for medium and larger sized motors are generally made of cast iron grids or grids consisting of an alloy of nickle and iron. The nickle alloy is generally preferred in the better class controls.

149. METHODS OF CONTROLLING THE SPEED OF D. C. MOTORS

The speed of shunt and compound motors may easily be controlled by the use of a rheostat in series with the shunt field, as shown in Fig. 119. By varying the resistance of the field rheostat, we can vary the current through the field of the motor. If the field is weakened, the counter-E. M. F. generated in the armature is momentarily reduced and more current is allowed to flow through the machine.

This will cause the machine to speed up until the counter-voltage produced in this weaker field is again normal. If the motor field is strengthened, the

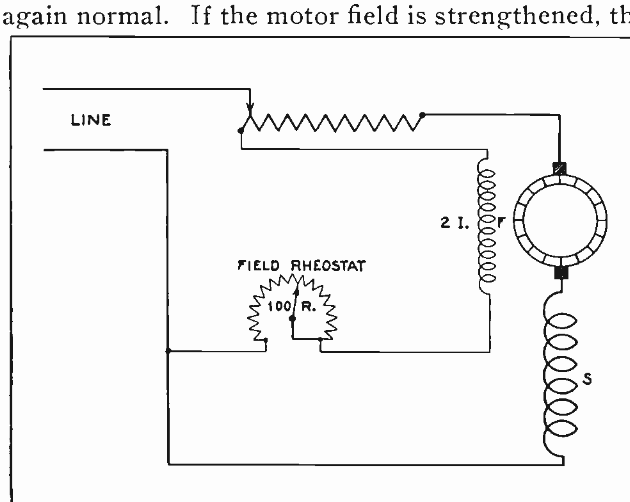

Fig. 119. This diagram shows the armature starting resistance and also a shunt field rheostat for varying the speed of the motor.

counter-voltage developed in the armature will be increased, and this will cause the current flowing through the machine to be reduced, allowing the speed to decrease until the counter-voltage developed in this stronger field is again normal.

It is possible to vary the speed of a motor only above its normal speed by the use of shunt field rheostats.

The torque of a motor armature will vary inversely with the speed when the field is weakened in the manner just described. The output in h. p., however, will remain approximately the same, as the h. p. is proportional to the product of the speed and torque.

For example, if a certain motor normally rotates at 1000 R. P. M. and develops 10 lbs. torque at the end of a brakearm, the product of this speed and torque is 1000×10, or 10,000.

Now, if we were to increase the speed of this motor to 2000 R. P. M., or double its normal speed, the torque, which varies inversely with the speed, will be reduced to 5 lbs., or one-half its former value. In this case, the speed times the torque equals 2000×5, or 10,000 as before.

Motors that do not have interpoles should not ordinarily be operated at speeds greater than 65 to 70 per cent above their normal speed ratings. On motors that have interpoles, it is possible to obtain speed variation as great as 6 to 1 ratio.

Field control is a very economical means of speed variation for D. C. motors, since the output of the motor in horse power remains practically unchanged and the power lost in the field rheostat is very small.

The power lost due to heating in any resistance is equal to the square of the current multiplied by the resistance, or $I^2 \times R = W$.

For example, let us assume that the resistance of the field rheostat shown in Fig. 119 is 100 ohms, and that the field current required by this motor is 2 amperes; then the power lost in the field rheostat would be $2^2 \times 100$, or 400 watts.

150. SPEED CONTROL BY USE OF ARMATURE RESISTANCE

The speed of shunt, series, and compound motors can also be regulated or varied by means of a rheostat in series with the armature, as shown in Fig. 120. An armature resistance used in this manner merely produces a voltage drop as the machine current flows through it, and thus it varies the voltage applied to the armature.

When this method of speed control is used, the strength of the shunt field of the motor is not varied, as it is connected directly across the line so it is not affected by the armature resistance. Observe this method of connection in Fig. 120..

When the voltage applied to the armature is decreased by cutting in the resistance of the armature rheostat, this will decrease the armature current and the speed of the motor. Since the torque of any motor varies with the product of the armature current and field flux, any change of this armature current produces a corresponding change in the torque and speed developed by the machine. When the motor slows down to a speed at which its counter E.M.F. and effective armature voltage again balance the applied voltage, the current and torque will again be the same as before changing the speed.

151. SPEED CONTROL BY FIELD RESISTANCE MOST ECONOMICAL GENERALLY

Speed control by means of armature resistance is very wasteful of power because of the very heavy armature current which must be passed through the rheostat, and the losses due to heat and I R drop in the rheostat.

If the armature shown in Fig. 120 requires 50 amperes for full load operation and the speed regulating rheostat has .5 of an ohm resistance, then the energy lost due to heat in the rheostat will be $I^2 \times R$, or $50^2 \times .5$, which equals 1250 watts.

If the field resistance were used for speed control of this motor, the losses would be much less. We will assume the field current to be 2 amperes, and the field rheostat resistance 100 ohms. Then the loss with this form of speed control would only be $2^2 \times 100$, or 400 watts.

The speed regulation of the motor which is controlled by armature resistance is very poor when the machine is operated below normal speed, while the speed regulation of a motor controlled by the field rheostat is very good, because the armature in this case is always operated at the same voltage.

Shunt field rheostats for ordinary motors are small compact devices, because they don't need to carry a great amount of current or to have a large heat radiating surface.

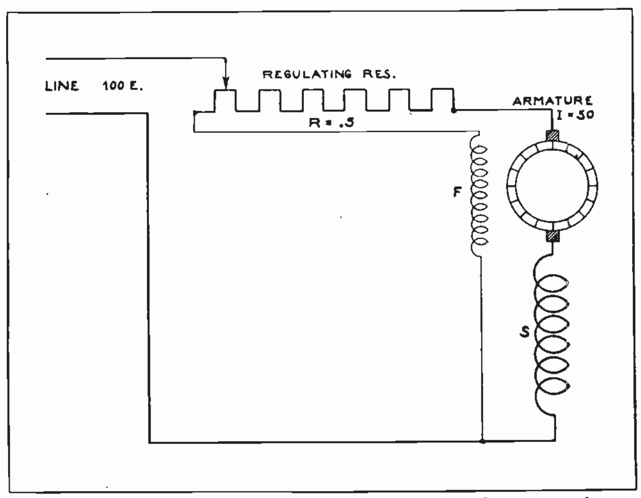

Fig. 120. Rheostats for speed regulating duty use heavier resistance units to stand the continued current load without overheating.

Armature rheostats are much larger and usually made of heavy cast iron grids, or, in the case of some of the latest type controls, they are made from alloy of manganese and copper.

From the foregoing material, it is easy to see that the use of the field rheostat provides a much more economical method of motor speed control than the

use of armature resistance, and it should therefore be used whenever possible.

The three principal advantages of field control over armature control are as follows:

1. The horse power output remains practically unchanged with field control but decreases considerably with armature control.
2. Power lost in the field rheostat is much lower than in armature rheostats, which must carry the heavier armature current.
3. The speed regulation of a motor which is controlled by field rheostats is much better than that of a machine controlled by armature resistance.

Resistance should never be cut in to both armature and field circuits at the same time on any motor, because resistance in the armature circuit tends to reduce the speed, while resistance in the field circuit tends to increase speed. So each one would tend to defeat the purpose of the other.

Both armature and field control are often used together on the same motor, however, **cutting out** resistance from the armature circuit to bring the speed from zero up to normal, and **cutting in** resistance in the field circuit to raise the speed above normal.

152. D. C. MOTOR CONTROLLERS

There are many types of D. C. motor starters and speed controllers, but the general principles of practically all of them are very much the same. Their function is usually to place resistance in series with the motor armature when the machine is started, and gradually cut out this resistance as the machine comes up to speed.

Some controllers also make a slight variation in the resistance in the shunt field circuit at the same time the armature resistance is cut out. Some types of controls have reversing switches or contacts in addition to the rheostat element, so they can be used for starting and reversing of motors.

The operation of controllers may be either **Manual** or **Automatic.** In the manual types the lever arm or sliding contact which cuts out the resistance is operated by hand; while, in automatic types, the movement of the sliding contact or switches which cut out the resistance is accomplished by means of electro-magnets or solenoids, which may be operated by a small push button switch located either at the controller or some distance from it. Because of this feature, certain controllers are known as **Automatic Remote-Control devices.**

The design of the various controllers depends in each case upon the size of the motors they are to operate and upon the class of duty they are to perform.

153. CONSTRUCTION FEATURES

Common small motor controls consist of a box or panel on which **are** mounted the stationary contacts and sliding contact or controller arm; and usually some form of latch or holding magnet to hold the arm in running position, and frequently some form of line switch or, possibly, reversing switch.

On some of the smaller type controllers these contacts, coils, and switches are on the outside of the box or on what is called a "face plate," made of slate or insulating material.

Controllers used for small motors frequently have the resistance coils mounted inside the box, directly behind the face plate. In such cases the box is usually of well-ventilated construction, to allow the heat to escape.

On larger controllers, the resistance coils or grids are frequently located in a separate box or on a panel, and have copper leads run from the contacts on the panel to the resistance element.

Modern automatic types of controls frequently have the entire assembly of magnets, switches, and contacts enclosed in a metal safety cabinet.

Regardless of the type or application of the controller, **you should be able to easily understand their** circuits and principles, with the knowledge you already have of electrical circuits, electro-magnets, switches and rheostats.

154. THREE AND FOUR POINT STARTERS

Some of the most simple and common types of controls used with shunt and compound motors are called 3-point and 4-point controllers. The names 3-point and 4-point are derived from the number of connections or terminals on the face plate of these controllers. The 3-point control is usually arranged for starting duty only, but in some cases it may also be used for speed control, if it is properly designed.

Fig. 121 shows the wiring and electrical connections of a simple 3-point starter. In this diagram all parts and connections are in plain view and the path of the armature current is marked with solid black arrows, while the field circuit is shown by the dotted arrows. Trace this circuit out thoroughly and become familiar with the principles and operation of this fundamental type of starter.

To operate a controller of this type and start the motor, the first step will be to close the line switch

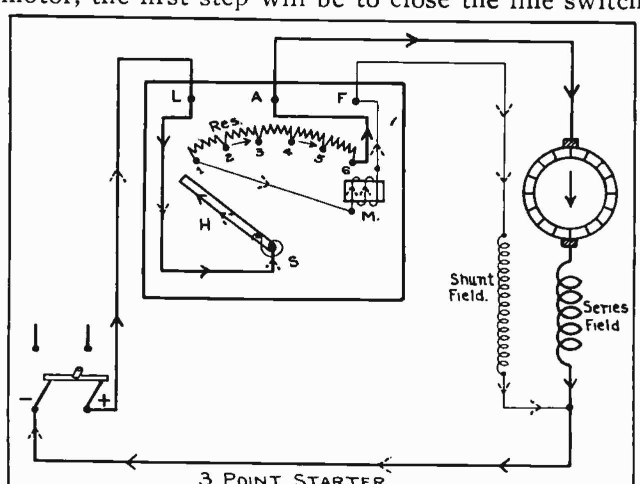

Fig. 121. This diagram shows the connections for a simple 3-point D. C. motor starter. Trace the circuit carefully with the accompanying instructions.

to apply the line voltage to the controller and motor.

You will note that one side of the line connects directly to the motor and that the controller is inserted in the other line wire, so that its resistance will affect both the armature and field circuits during starting.

The first step after closing the line switch is to move the lever arm "H" to the first point or contact attached to the left end of the controller resistance. Current will then start to flow from the opposite line wire, through the controller arm, and through the entire resistance to the motor armature and series field, and then back to the negative line wire, as shown by the solid arrows.

Another circuit can also be traced from the lever arm when it is in contact with point No. 1, as the current divides at this point and a small amount flows through the holding magnet "M", then through the shunt field winding and back to the negative line wire, as shown by the dotted arrows.

As soon as the motor starts to turn, the controller arm can be moved slowly across the contacts in order, 1, 2, 3, etc. This cuts out the resistance from the armature circuit step by step as the armature develops speed and begins to generate counter-voltage.

When the last contact point is reached, all resistance has been cut out of the armature circuit, and the lever arm will be held in this running position by the holding magnet "M", which is in series with the shunt field circuit.

155. "NO VOLTAGE" and "NO FIELD" RELEASE COIL

The reason for connecting this holding magnet in series with the motor field is to provide what is known as **"no field" protection.**

We have learned that a motor with a very weak field is likely to overspeed dangerously. This would probably be the case if an open circuit should occur in the shunt field coils or connections of a motor of this type, when it is not loaded.

However, with the holding magnet, "M", connected in series with the shunt field, if any break occurs in this circuit the magnet, "M", will be de-energized and allow the controller arm to be thrown back to the "off" position by means of a spring. This will stop the motor before it has a chance to overspeed.

This holding magnet also acts as a "no voltage" release, so that if the voltage or power supplied at the line should fail, the starter arm will be released and return to normal position and thus stop the motor.

If this protection were not provided and the controller arm were left in running position, the motor might be burned out or injured when the power came back on the line, because there would then be no resistance in series with the motor armature.

This holding magnet is often referred **to as a no-field or no-voltage release coil,** and provides this very important protection to the motor, **in addition to** serving its function of holding the starter **arm in** place.

156. ALL RESISTANCE OUT OF FIELD CIRCUIT DURING STARTING

You will note by tracing the circuit when the starter arm is in the running position, that the field current will then have to pass back through the entire starter resistance, **through coil "M", and the** shunt field. We find, therefore, that as the controller cuts the resistance out of the armature circuit, it places the same resistance in the shunt field circuit. The advantage of this is that it provides maximum strength of the shunt field during starting of the motor, when it is naturally desired to provide the best possible starting torque.

As the motor comes up to speed, the shunt field strength can be reduced to normal by causing its current to flow through the starter resistance.

The value of the armature resistance in ohms is very low and it therefore doesn't affect the shunt field as much as it does the armature, because the very small current required by the shunt field doesn't create much voltage drop when flowing through this resistance.

157. STOPPING A MOTOR

To stop the motor, we should always open the line switch, which will interrupt the current flow through the armature and field, and also allow the controller arm to fall back to starting position.

Never attempt to stop a motor by pulling the controller arm back across the contacts while the line switch is closed.

This would cause severe arcing and damage to the controller contacts, which should always be kept smooth and in good condition.

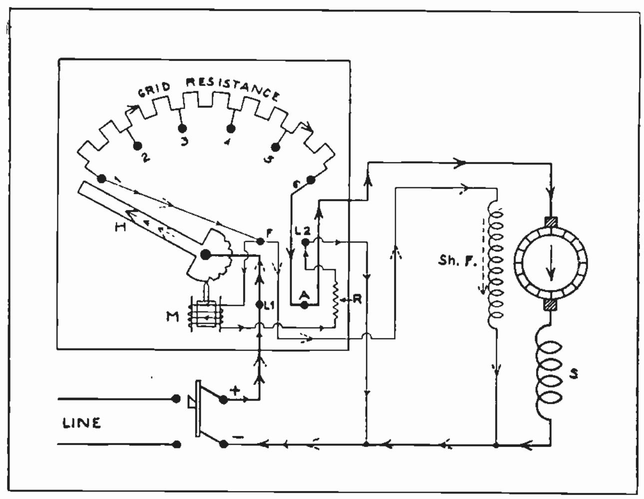

Fig. 122. Wiring diagram of a 4-point starter for speed regulating. Observe the connections and operating principle carefully.

158. STARTER TERMINALS AND CONNECTIONS

You will note in Fig. 121 that the terminals on the starter are marked L, A, and F, to indicate the connections for the line, armature, and field. This makes it a very simple matter to connect up controllers of this type to the line and motor.

The principal point to keep in mind is that one line wire should connect directly to the motor, being attached to both the shunt field and armature, or series field leads. The other side of the line should connect to the line terminal on the controller, and the remaining armature and field leads of the motor should connect respectively to the armature and field terminals on the controller. These terminals are usually marked on the controller or on the blue print supplied with it by the manufacturers.

159. SPEED REGULATING CONTROLLERS

Fig. 122 shows a 4-point controller of the type which can be used both for starting and speed regulation of D. C. motors. The resistance element of this controller is made of heavier grids of iron or nickle alloy, and is designed to carry the full armature current of the motor for indefinite periods.

The principal differences between this controller and the one shown in Fig. 121 are the larger resistance element, the use of 4 terminal points instead of 3, and the arrangement of the holding magnet, "M". With this speed-regulating controller, the lever arm and holding magnet are mechanically arranged so that the arm can be held in any position between No. 1 and 6 on the resistance contacts.

This allows the arm to be set for any desired speed of the motor. In this case, both line wires are connected to the controller terminals marked "L-1" and "L-2". The reason for connecting the negative line wire to the controller at "L-2" is merely to complete the circuit of the holding coil "M", directly across the line.

The small resistance "R" is placed in series with the magnet coil to keep it from overheating.

The armature path of current in Fig. 122 is shown by the large solid arrows, the shunt field current by the dotted arrows, and the current through the holding coil "M", by the small solid arrows. Trace each of these circuits out very carefully to be sure you thoroughly understand the operation of this controller.

Fig. 123 shows two views of a simple motor starter of the 3-point type. The view on the left shows the starter completely enclosed in the safety box with just the handle projecting from the front cover. When the cover is closed this handle connects with the sliding contact arm inside the box. The view on the right shows this arm as well as the stationary contacts and holding magnet.

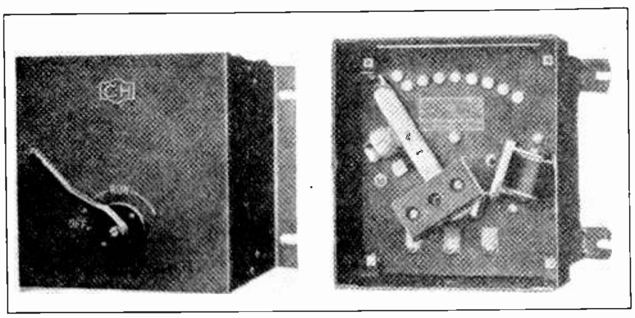

Fig. 123. Photo of a simple 3-point starter enclosed in a metal safety box.

Where small, low priced starters of the type just described are used, fuses are generally used with them to provide overload protection for the motors. Sometimes these fuses as well as the line switch are enclosed in the same box with the starter, as shown in Fig. 124..

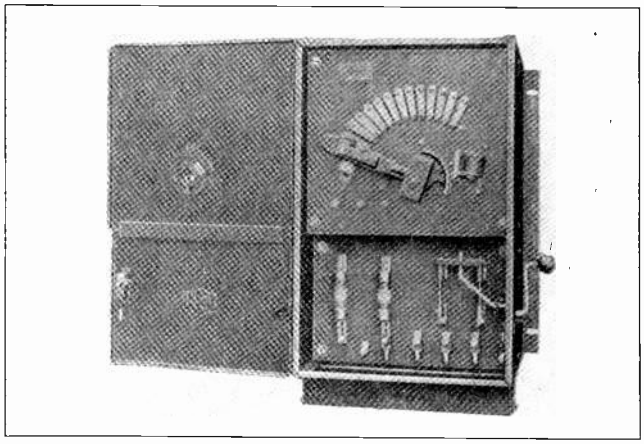

Fig. 124. Speed regulating controller with fuses and line switch enclosed in a controller box.

The switch in this case is also operated by a safety handle on the outside of the box.

Fig. 125 shows three forms of resistance elements such as are commonly used with motor starters. In the lower view, the resistance wire is wound on insulating forms of heat-resisting material, and then coated over with a plaster-like substance of the same nature. Note how a number of these coils can be mounted on a rack and spaced to allow ventilation. We can then connect several such units or coils in series or parallel, as desired, to obtain the proper resistance with convenient standard units.

The view on the upper right shows a heavy-duty resistor made in the form of grids. These grids are clamped together with bolts as shown, and are spaced with washers of porcelain or some other insulating and heat resisting material.

Resistance coils are frequently wound on tubular shapes or forms, and mounted in the starter box, as shown at the upper left in Fig. 125. The copper wires or leads shown attached to these coils are used for connecting them to the stationary segments or contacts on the starter plate.

160. CARBON PILE STARTERS

In some classes of work, such as the operation of textile mill machinery and certain other equipment, it is desirable to have very gradual application of the starting torque of the motor when the machines are first put in motion.

To accomplish this, it would, of course, be necessary to start the motor with extremely high resistance in the armature circuit, so that the starting current could be limited to only a very small fraction of the load current. For this purpose, some starters are made with resistance elements consisting of small carbon disks stacked in tubes of non-combustible material with an insulating lining, as shown in the left-hand view in Fig. 126.

As long as these carbon disks are left loose in the column or tube, the resistance through them is very high, because of the loose contact between each disk and the next. If pressure is gradually applied to the ends of this column by means of a lever and spring, this tightens the contacts between the disks and very gradually reduces the resistance through the pile.

One or more of these tubular piles or resistance elements can be arranged in a starter as shown in the right-hand view of Fig. 126; so that pressure can be smoothly applied to them by means of the lever shown in this view. Starters of this type are known as **carbon pile starters,** and they afford a means of starting motors more gradually and smoothly than with practically any other device on the market.

161. SMOOTH STARTING OF MOTORS WITH CARBON STARTERS

When using a starter of this type, there is practically no sudden increase in the starting current through the motor, as there is when the lever arm of the "step by step" starter is shifted from one contact to the next.

In addition to the pressure-applying device in starters of this type, there must also be some form of switch or contactor to short circuit the carbon piles entirely out of the armature circuit after full pressure has been applied and the machine is up to speed. The reason for using this short-circuiting switch is that the resistance of the carbon pile is still too high to leave in the motor circuit, even when the disks are under maximum pressure; and they would tend to overheat if left in the circuit too long.

Tubes with larger disks are provided, however, for use with speed-regulating controllers, and these can be left in the circuit while the motor is running.

Two or more of these carbon pile tubes can be connected in series or parallel to obtain the proper current-carrying capacity of different controllers. If the disks

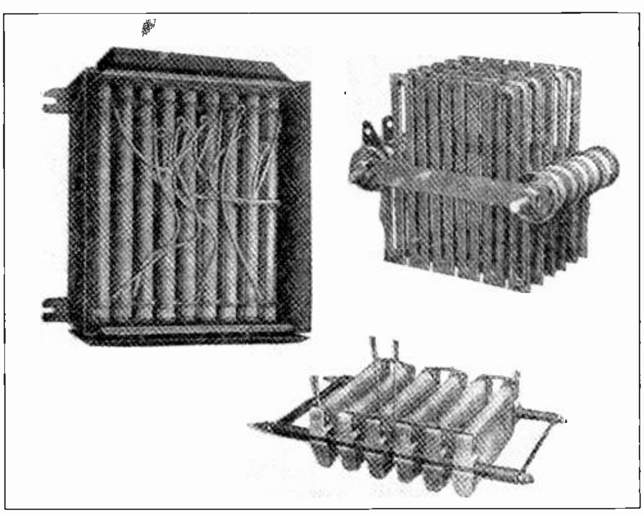

Fig 125. Several styles of resistance units commonly used with motor starters and speed controls.

become worn or damaged at any time, they can easily be replaced by removing the tubes from the controller and replacing with complete new tubes; or the end plug can be removed from any tube and the disks taken out, so that one or more of those which may be damaged or cracked can be replaced.

Carbon pile controllers are also made in automatic types as well as those for manual operation.

Motor controllers are made in various h. p. ratings, and when purchasing or installing them, care should be used to see that they are of the proper size to carry the current for the motor which they are operating, without overheating of the resistance elements or burning the contacts.

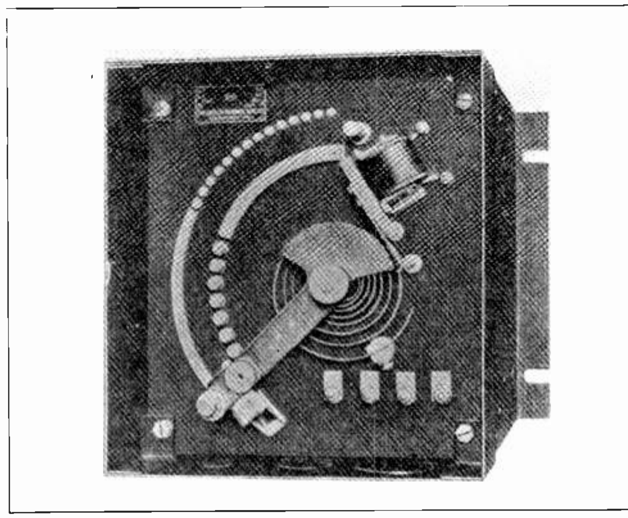

Fig. 125-A. Simple type of D. C. motor starter and speed control. Note the extra sets of contacts for the field resistance used in varying the speed.

162. CIRCUIT OF A CARBON CONTROLLER

Fig. 127 shows the circuit of a simple, manual-type, carbon pile, motor starter. In this diagram the path of the armature current is shown by the solid arrows and can be traced from the positive line wire through the armature of the starter to contact 1. From this point, the armature current flows through the lower wire to the bottom of the carbon pile, up through the carbon disks, out at the top through a flexible lead, on through the armature and series field, and back through the negative line wire.

As soon as the starter arm makes contact with 1, field current can also flow, as shown by the dotted arrows from the positive line, through the starter arm; and from contact 1 the current flows up through the curved brass strip, through the holding coil, "M"; through the shunt field; and then back through the negative line wire.

As the starter arm is moved slowly upward, it applies more and more pressure to the carbon disks by means of the hook and spring shown in the figure. When the starter arm reaches contact 2, full pressure has been applied to the carbon disks; and the arm, upon touching contact 2, short-circuits the carbon pile out of the armature circuit.

The current then flows from the starter arm to contact 2, out at the armature terminal "A" through the motor, and then to the negative line wire.

163. AUTOMATIC STARTERS

As previously mentioned, a great number of motor starters and controllers are equipped with solenoids or electro-magnets which operate the switches or arms which cut out the starting resistance as the motor comes up to speed. This type of construction eliminates manual operation of the controller and reduces liability of damage to motors and controllers by improper use when controllers are operated manually by careless operators.

If a manual starter is operated too rapidly and all of the resistance is cut out before the motor comes up to speed, or if the starter is operated too slowly thus leaving the armature resistance in the circuit too long, it is likely to damage both the controller and the motor.

Automatic controllers which are operated by solenoids or electro-magnets usually have a time control device, in the form of a dash-pot attached to the solenoid or starter arm. By the proper adjustment of the dash-pot, the controller can be set so that it will start the motor in the same period of time at each operation.

Other controllers have the time period which they are left in the circuit regulated by the armature current of the motor so that the resistance cannot all be cut out of the circuit until the starting current has been sufficiently reduced by the increased speed of the motor.

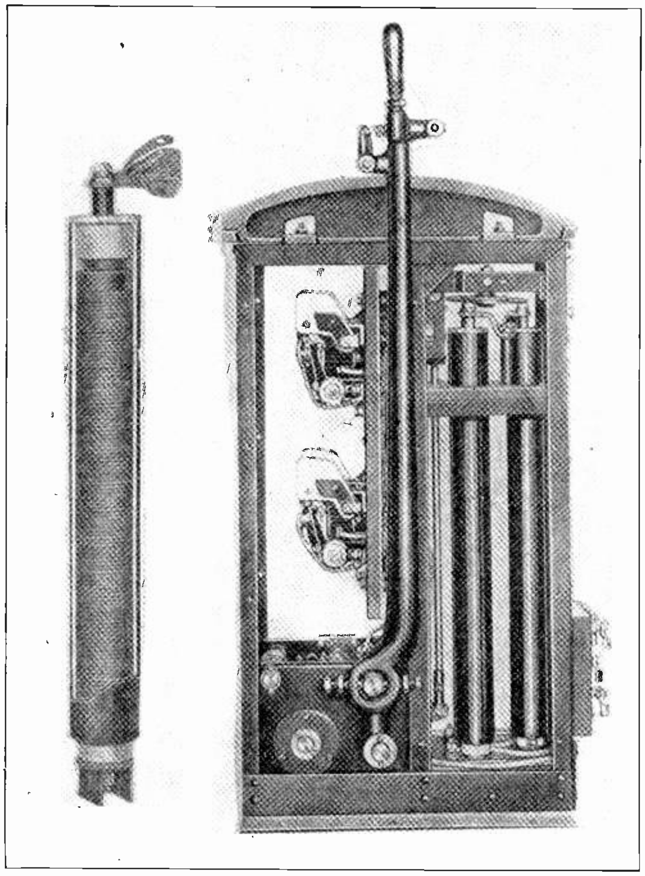

Fig. 126. Carbon-pile rheostat for starting D. C. motors very gradually. On the left is shown one of the carbon resistance elements used with such starters.

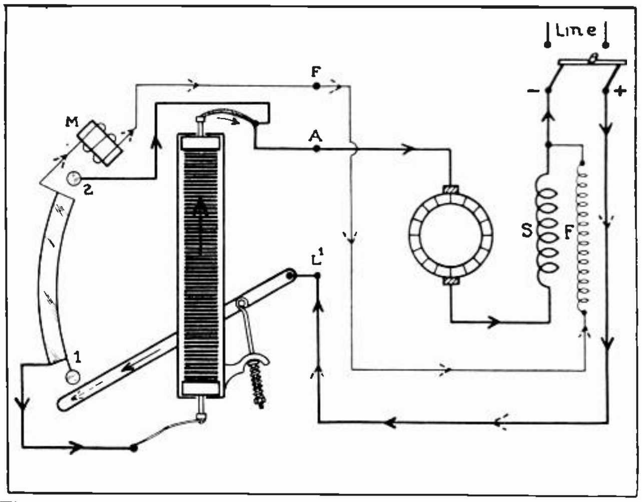

Fig. 127. Wiring diagram for a carbon-pile motor starter. Trace this circuit carefully.

164. REMOTE CONTROL

Another great advantage of magnetically operated controllers is that they can be controlled or operated from a distance by means of push-button switches which close the circuit to the operating solenoids or magnets.

For example, a motor located in one room or on a certain floor of a building can be controlled from any other room or floor of the building. Elevator controls are a good example of the use of remote control equipment. Elevator motors are usually located on the top floor of the building and are controlled by a switch in the car of the elevator which merely operates the circuits of the magnets or solenoids on controllers located near the motors.

Remote control devices can be used to improve the safety of operation of many types of machinery driven by electric motors. Push buttons for stopping and starting the motor which drives a machine can be located at several convenient places around the machine, so that they are always within reach of the operator in case he should become caught in any part of the running machinery.

Automatic and remote types of controllers are, of course, more expensive to install, but they will usually save considerably more than the difference in their first cost, by increasing the life of the motor and control equipment, and by reducing repair bills which are caused by careless operation of manual starters.

There are many types of automatic starters on the market and in use, but their general principles are very much the same; so you should have no difficulty in understanding or installing any of the common types, if you will make a thorough study of the principles covered in the following pages.

165. OPERATION OF AUTOMATIC CONTROLLERS

Fig. 128 shows a diagram of an automatic starter which uses a solenoid coil at "S" to draw up an iron core or plunger and at the same time raise the contact bar "B", which in this case takes the place of the lever arm used on the previously described controllers.

This controller is arranged for remote control by means of the stop and start push buttons shown at the upper right-hand corner. When the "start" button is closed, it completes a circuit through the solenoid coil, as shown by the small dotted arrows.

Trace the circuit of this controller in Fig. 128 very carefully while reading the following explanation.

Assuming the line switch to be closed when the start button is pressed, current will flow as shown by the small dotted arrows from the positive line wire, through the solenoid coil and contacts "B", which are closed at this time; leaving the controller at terminal 1 and passing throught the closed circuit stop switch, through the starting switch, and back to terminal 3,

From this point, it passes through a wire inside the controller to terminal L-2 and back to the negative line wire, thus completing the solenoid circuit. This energizes the solenoid coil and causes it to lift its plunger and raise the upper main contact bar "B".

This bar is prevented from rising too rapidly by a dash-pot attached to the solenoid plunger. The dash-pot consists of a cylinder in which are enclosed a piston and a quantity of oil. As the piston rises it presses the oil before it and retards the motion of the plunger, allowing it to move upward only as fast as the oil can escape around the edges of the piston, or through a by-pass tube which is sometimes arranged at the side of the cylinders.

As soon as the solenoid plunger starts to rise, it allows the spring contact "A" to close and complete the "holding" circuit through the solenoid, without the aid of a start button.

The start button then can be released and current will continue to flow through the solenoid, as shown by the small solid arrows, causing it to continue to draw up the plunger.

As the plunger moves up a little further, the copper contact bar "B" touches the contact finger or spring 1,

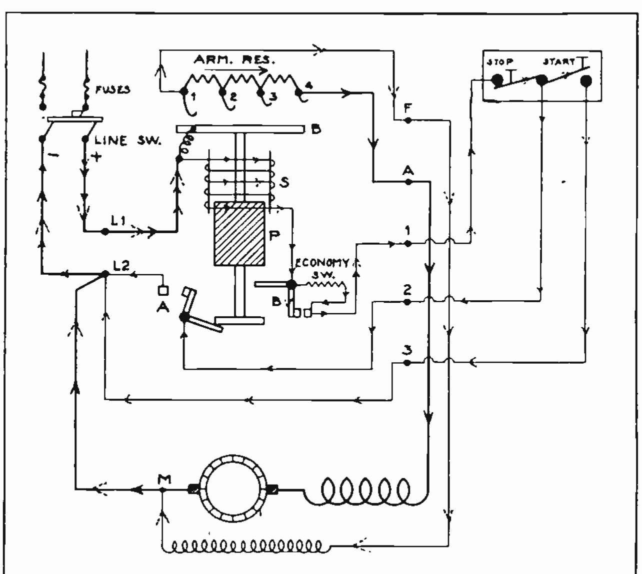

Fig. 128. This diagram shows the wiring for an automatic starter of the solenoid type. Trace each circuit until you thoroughly understand the operation of this controller.

which connects to the first step of the armature resistance. This allows current to flow as shown by the large solid arrows, from the positive line wire and line terminal "L-1", through the flexible connection to bar "B", contact spring No. 1, then through the full armature resistance to armature terminal "A", series field, motor armature, back to terminal "L-2", and the negative line wire.

A circuit can also be traced throught the shunt field of the motor, as shown by the large dotted arrows.

As the solenoid continues to draw the plunger slowly upward, the bar "B" next makes contact with springs 2, 3, 4 in succession, thus short circuiting and cutting out the armature resistance one step at a time.

When the bar touches contact spring 4, the current will flow directly from the bar to terminal "A", and through the motor armature, without passing through any of the starter resistance.

166. ECONOMY COIL

The small auxiliary switch shown at "B" below and to the right of the solenoid in Fig. 128 is for the purpose of cutting a protective resistance in series with the solenoid coil, after the plunger has been raised to the top of its stroke. When the plunger reaches this point, it will lift the arm of this switch, causing the contacts to open.

The current required to hold the plunger in position once it is up is much less than the current required to start it and pull it up. This smaller holding current will flow through the economy resistance, instead of through the contacts at "B", as it did while starting.

Cutting in this economy resistance not only saves current but prevents the solenoid coil from becoming overheated when it holds the controller in operation for long periods. The economy resistance will usually reduce the current flow through the solenoid coil to one-half or less than one-half its value during starting.

167. STOPPING THE MOTOR

To stop the motor with a controller of this type, it is only necessary to press the stop button. This breaks the holding circuit through the solenoid coil and allows the plunger to fall. The plunger is permitted to fall rapidly by means of a flap valve, which allows the oil to escape rapidly when the piston moves in a downward direction. When the plunger reaches the bottom of its stroke, it trips open the switch "A" in the holding circuit; so it will then be necessary to close the starting switch to energize the solenoid once more. The motor can also be stopped by opening the line switch.

Fig. 129 shows the front view of a solenoid-type starter very similar to the one just described. The spring contact-fingers which cut out the armature resistance are slightly different on this starter than on the bar and spring type illustrated in the diagram, but their electrical principle is identically the same.

Beneath the solenoid in Fig. 129 can be seen the oil dash-pot which slows the operation of the

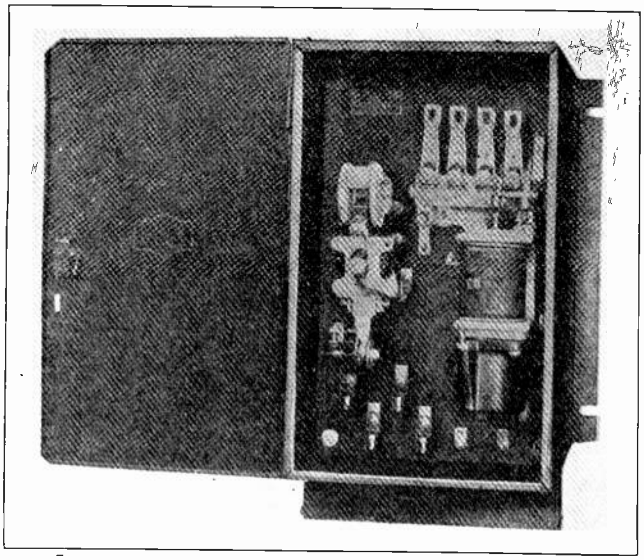

Fig. 129. Photo of a solenoid operated motor starter. Note the arrangement of the contact fingers and also the main line contactor on the left, and the oil dash-pot on the solenoid.

plunger, and on the left side of this dash-pot is shown a small adjusting screw by which the speed of the plunger operation can be varied as desired.

Fig. 130 shows several types of push-button stations such as are used with remote controllers.

168. DASH-POTS FOR TIME DELAY ON CONTROLLERS

Fig. 131 illustrates the principle of the dash-pot timing device used with many automatic starters. When the plunger rod "R" is drawn up by the solenoid, the piston on the lower end of this rod lifts the oil by the suction of the piston and forces it through the needle valve "V", and around into the lower part of the cylinder.

The speed with which the plunger will rise can, therefore, be adjusted by means of the screw of the needle valve, which will allow the oil to pass more or less rapidly through this opening.

During the period that the piston is lifting against the oil, the disk "D" holds tightly against the openings or ports at "P" in the piston. When the line switch is opened or the stop button is pressed, allowing the plunger to fall, the pressure on the under side of the piston forces the disk "D" to open the ports at "P", and allows the plunger to fall very rapidly.

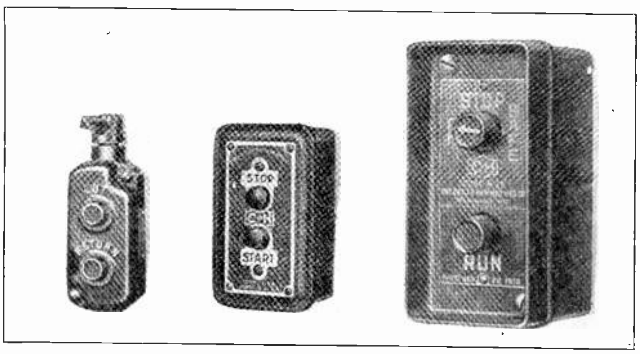

Fig. 130. Several types of push-button stations used with automatic remote controllers.

This dash-pot time-delay device should be carefully adjusted, according to the load on the motor and the time required for the motor to accelerate this load to full speed.

169. MAGNETIC STARTERS

The term **magnetic starter** is commonly used to apply to starters on which the operation depends almost entirely on relays, although they may have either a solenoid or an electro-magnet for overload protection.

Controllers of this type have a number of separate contactors, each operated by its own electro-magnet. These contactors and their circuits are so arranged that they operate in succession, and thus gradually short out resistance from the motor armature circuit.

Controls of this type are used very extensively on large industrial motors, steel mill motors, elevator motors, etc.

On medium-sized motors, the controller mechanism and contactors are often assembled inside the metal box or cabinet. For very large motors the contactors and magnets are usually assembled on a panel similar to a switchboard, and the resistance grids or elements are generally located at the rear of this panel, either on the floor or in a special rack above.

Fig. 132 shows a diagram of a magnetic controller. This controller operates as follows:

After closing the line switch, either of the start buttons at the remote control stations can be pressed to close a circuit through the remote control relay "A", as shown by the small dotted arrows.

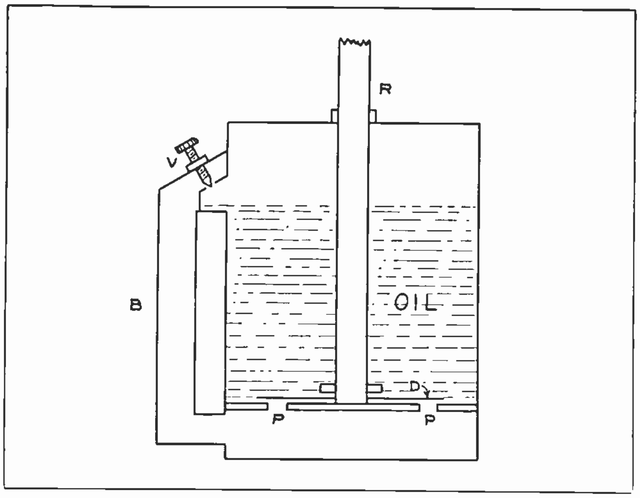

Fig. 131. The above sketch illustrates the principle of an oil dash-pot used as a time control on motor starters.

This relay magnet then attracts its double armature and closes contacts 1 and 2. Contactor 2 completes a holding circuit through relay "A" in series with the stop switches of the remote control stations. This circuit is shown by the small solid arrows.

The same contactor, No. 2, also completes a circuit through relay "B", as shown by the small curved arrows.

The current for this relay passes through the lower portion of the armature resistance and doesn't close contactor 4 immediately. Current for coil "B" is limited by the voltage drop in the armature resistance.

Contactor 1, which was operated by relay "A", closes a circuit through the overload release coil, "O. L.", to the motor terminal "M", as shown by the large dotted arrows. At this point the current divides and passes through both the armature and field circuits in parallel, and through the controller back to the negative line wire.

The armature current shown by the solid black arrows returns through the terminal "A-1" on the controller, through the winding of relay "F" and armature starting resistance in parallel. This current divides through the relay winding and armature resistance in proportion to the resistance of each path. As the relay winding is of much higher resistance than the armature resistance unit, most of the current will pass through the armature resistance and back to the line. However, enough current flows through the winding of relay "F" to cause it to become energized and close contactor 3, which short circuits the field rheostat, "F R", cutting this resistance out of the shunt field circuit of the motor.

The armature resistance used with this controller performs the same function as with any other type, namely that of causing a voltage drop and reducing the current flow through the motor armature during starting.

When contactor 3 is closed, the shunt field of the motor is connected directly across full line voltage, thus allowing the shunt field to receive full strength current and produce the good torque necessary for starting.

170. TIME OF STARTING DEPENDS ON STARTING CURRENT

We recall that relay "B" didn't energize when the circuit through its coil was first closed because it is in series with about one-third of the armature resistance. Therefore, as long as the heavy starting current is flowing through this armature resistance and causing considerable voltage drop, part of that voltage drop being in series with the coil of relay "B", limits its current and prevents it from becoming strong enough to close its armature.

As the motor comes up to speed and develops counter-E. M. F., thereby reducing the starting current through the armature resistance, this will also reduce the voltage drop through that section of the resistance which is in series with coil "B". This allows the current through coil "B" to increase slightly and causes it to close contactor 4. When this contactor closes it places a short circuit on the coil of relay "F", which can be traced from X to X-1, and

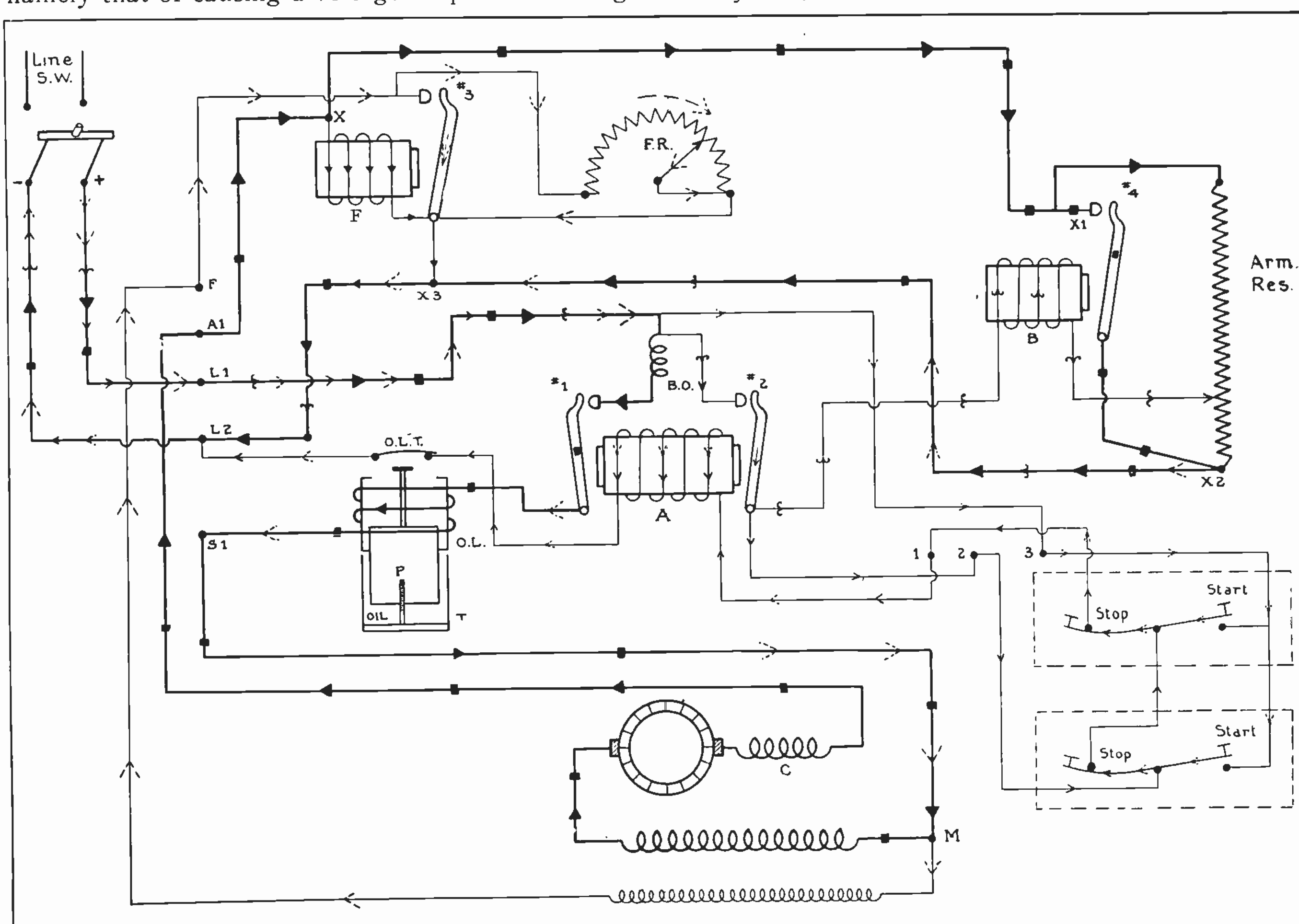

Fig. 132. This diagram shows the complete wiring of a modern magnetic type controller. You will find it very interesting and exceedingly well worthwhile to trace each circuit and obtain a thorough understanding of the operating principles of this starter.

X-2 to X-3. This shorts the current around the coil of relay "F" and causes it to de-energize and release contactor 3.

When this contactor opens, it releases the short circuit on the field rheostat, "F. R." and places this resistance back in series with the shunt field of the motor. This allows the motor speed to make its final increase for the starting operation, and also allows the field rheostat to be used for regulating the speed of the motor.

Contactor 4 is adjustable and can be set to pull in on any desired voltage within the range of this controller. By adjusting the screws to allow the relay armature to normally rest farther away from the core, it will require a higher voltage to operate this contactor.

This means that the motor will have to reach a little higher speed, develop more counter-E. M. F., and further reduce the starting current flowing through the armature resistance, and thereby reduce the voltage drop, allowing a higher voltage to be applied to the coil of relay "B" before it will operate.

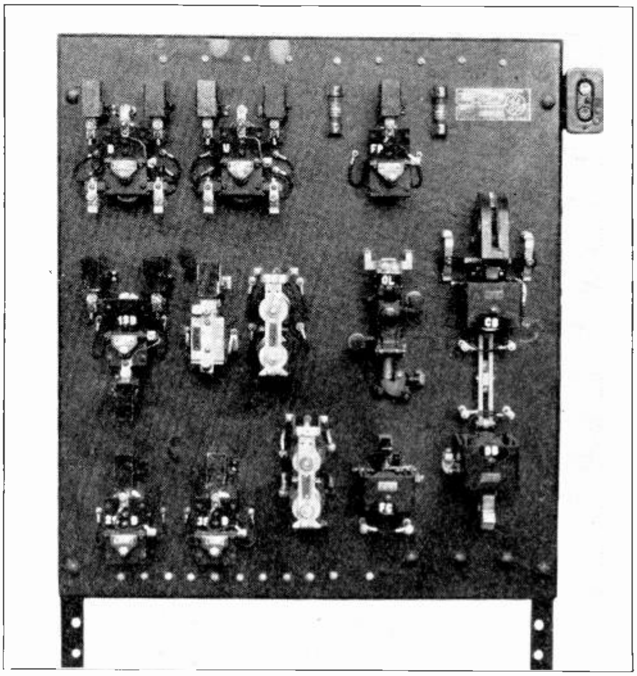

Fig. 132-A. This photo shows the manner in which the magnetic contactors of industrial controls of the larger type are often mounted on an open panel.

When this relay does operate, it short-circuits the armature resistance completely out of the motor circuit by providing a path of copper around the resistance from X-1 to X-2. So we find that the time delay on this relay and controller depends upon the reduction of the starting current through the motor armature and the armature resistance of the controller.

Therefore, if the motor is more heavily loaded at one time of starting than at another and requires longer to come up to full speed and develop the proper counter-voltage, this controller will automatically leave the armature resistance in series that much longer. For this reason it is a very practical and dependable type of control.

After the motor is up to full speed and the controller starting operation completed, the armature current will then be flowing through the circuit as shown by the square dots.

171. OVERLOAD PROTECTION

In tracing this circuit you will find that the armature current passes continuously through the coil of the overload relay "O. L." as long as the motor is in operation.

The purpose of this overload relay, which is included with many controllers of this type, is to protect the motor from overload, both during starting and while the motor is running at full speed.

The coil of this relay is in series with the motor armature and therefore consists of a very few turns of heavy conductor capable of carrying the full armature current for indefinite periods.

If an overload is placed on the motor, thereby increasing its armature current, the increased current will increase the strength of the coil of the overload-relay solenoid.

This will cause it to draw up the plunger "P" slowly against the action of the oil in the dash-pot "T". This dash-pot can be so adjusted that it will require more or less time for the plunger to complete its upward stroke, and so that an overload which only lasts for an instant does not raise the plunger far enough to stop the motor.

The dash-pot is often called an **inverse time limit device,** because the time required to draw up the plunger is inversely proportional to the current or amount of overload on the motor. A severe overload

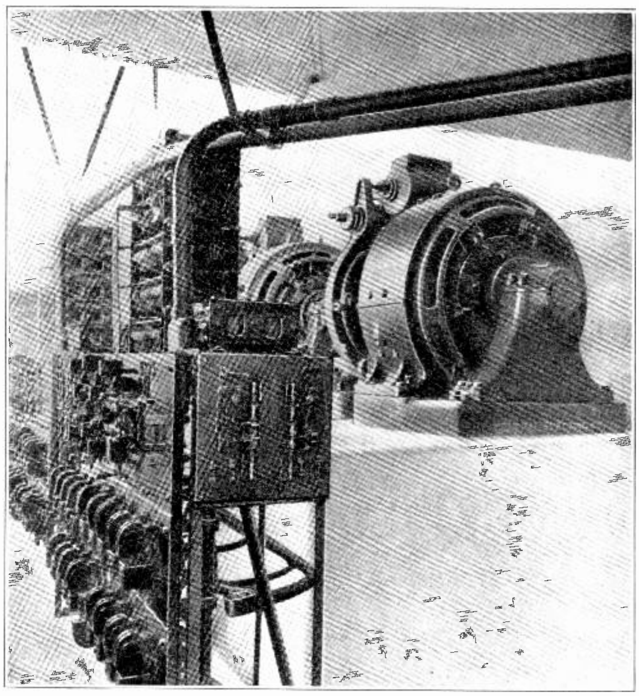

Fig. 132-B. Photo of the control panels for a group of elevator motors. Note the contactors on the face of the panel and the resistance grids located above.

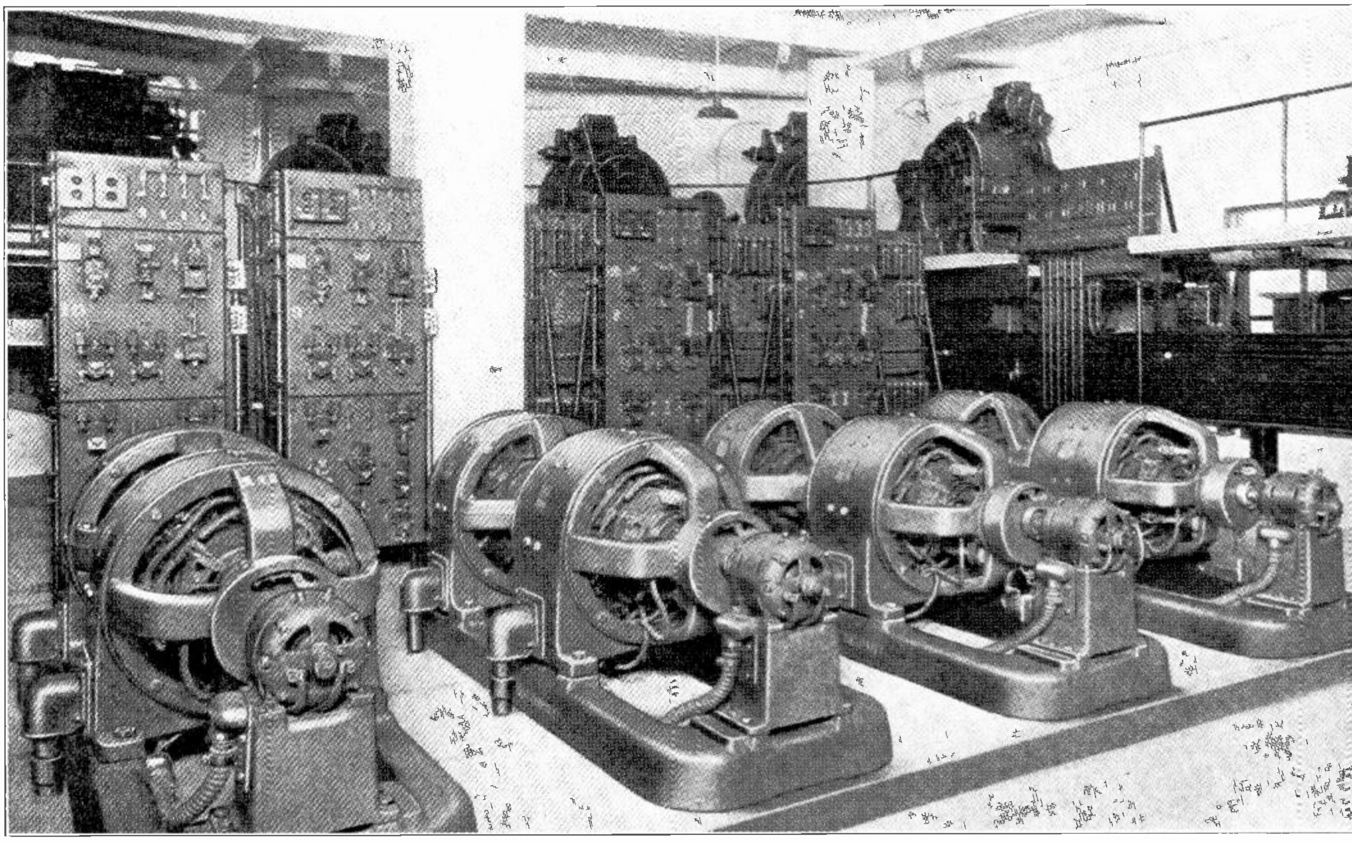

Fig. 132-C. This view shows the control panels for a group of modern elevator machines of the motor-generator type. The magnetic contactors on these panels are operated by remote control from the elevator car.

increases the strength of the coil to such an extent that the plunger will come up very quickly.

If the overload remains on the motor, the plunger will be drawn up completely until it strikes the overload-trip-contact, "O. L. T.". This opens the circuit of the relay coil "A", allowing it to release both its armatures and contactors 1 and 2.

When contactor 1 is opened, it disconnects the motor from the line, and 2 breaks the holding circuit of coil "A", requiring it to be closed again, by means of the start buttons, after the overload on the motor is removed.

172. "BLOW-OUT" COIL

The magnetic blow-out coil, "B. O." is for the purpose of providing a strong magnetic flux for extinguishing the arc drawn at contactor 1 when the motor circuit is broken at this point.

The action of this blow-out coil is purely magnetic. The few turns of which it consists are wound on a small iron core, which has its poles placed on either side of the contacts where the circuit will be broken. This provides a powerful magnetic field at the exact point where an arc would be formed when the circuit is broken by this contactor.

As the arc is in itself a conductor of electrical current and has a magnetic field set up around it, this field will be reacted upon by the flux of the blow-out coil and cause the arc to become distorted or stretched so that it is quickly broken or extinguished. This prevents the arc from lasting long enough to overheat and burn the contacts to any great extent.

Regardless of the extent of the overload, the magnetic blow-out coil is very effective, because the entire load current of the motor flows through its turns and its strength is therefore proportional to the current to be interrupted at any time.

Fig. 133 illustrates the principle and action of this blow-out coil on an arc drawn between two contacts which are located between the poles of the magnet.

In the view at the left, the solid lines between the contacts "A" and "B" represent the arc and the current flowing through it, while the dotted lines between the magnet poles represent the strong flux which is set up by them.

In the view at the right, the circle and dot represent an end view of the arc, and the direction of the flux around the arc is shown by the three arrows. The dotted lines show the magnetic flux from the poles of the blow-out magnet.

By noting the direction of this flux and that around the arc, we find that the lines of force will tend to be distorted as shown, and will stretch the arc out of its normal path in the direction shown by the dotted arrow.

The circuit of a controller such as shown in Fig. 132 may at first seem rather complicated, but you will find after carefully tracing through each part of it several times, that its operation is exceedingly simple. It is only by tracing such circuits as these, both in the diagrams and on the actual equipment, that you will be able to fully understand the operation of controls of this type and become competent in testing their circuits to locate any troubles which may develop in them.

This diagram and the explanation given in the accompanying paragraphs are, therefore, well worth thorough and careful study.

The controller shown in Fig. 132 uses a field rheostat for controlling the speed of the motor. This rheostat can be adjusted, or set at various points, by hand.

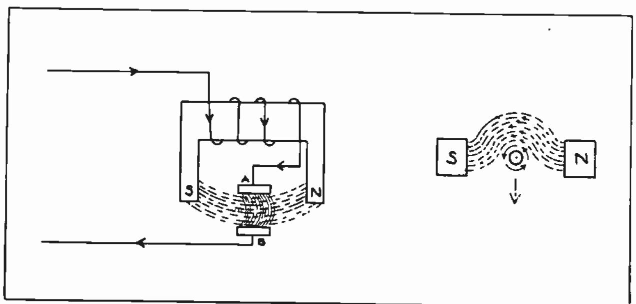

Fig. 133. The above sketch illustrates the principle by which the magnetic blow out coil extinguishes arcs on controller contacts.

Fig. 134 shows a magnetic type of controller very similar to the one for which the circuit is shown in Fig. 132. The several magnetic contactors and overload trip coil can be see mounted on the panel in the cabinet. This view, however, does not show the field rheostat for speed regulation.

173. DRUM CONTROLLERS

Drum controllers are very extensively used in the operation of D. C. motors where it is required to be able to start, stop, reverse, and vary the speed of the motors. The name **drum controller** comes from the shape of this device, and the manner in which the contacts or segments are mounted on a shaft or drum. This cylindrical arrangement of the contacts is made in order that they may be rotated part of a turn in either direction and brought into connection with one or more sets of stationary contacts.

Drum controllers are usually manually operated and can be provided with almost any number and desired arrangement of contacts. Drum controls are extensively used for controlling the motors used on street cars and electric trains, cranes, hoists and machine-tool equipment, where it is necessary to be able to reverse and vary the speed of the motors.

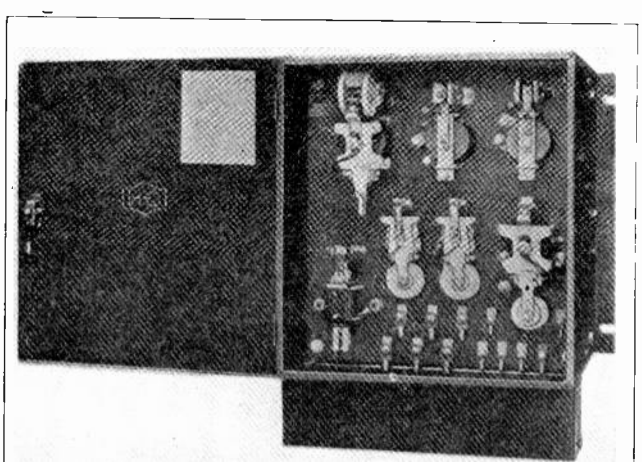

Fig. 134. Photo of an enclosed type magnetic starter for small and medium sized motors.

174. OPERATION OF SIMPLE DRUM CONTROL

Fig. 135 shows a very simple form of drum control and illustrates the manner in which the movable drum contacts can be used to short out the armature resistance step by step from the motor circuit. When the drum shown in this figure is rotated the first step and brings the movable segments "A" and "B" into connection with the stationary contacts, current will start to flow through the entire set of resistance coils, through segments "B", and the jumper which connects it to "A", through segments "A" to contact 1; then through the motor armature and back to the negative side of the line.

When the drum is rotated another step to the left, segment "C" touches contact 3, and as "C" is connected to "B" by the jumper, this short circuits the resistance between contacts 3 and 2.

Rotating the drum two more steps will short out the remaining two sections of resistance in the same order. Thus a simple drum-control can be used to gradually cut out the resistance as the motor comes up to full speed.

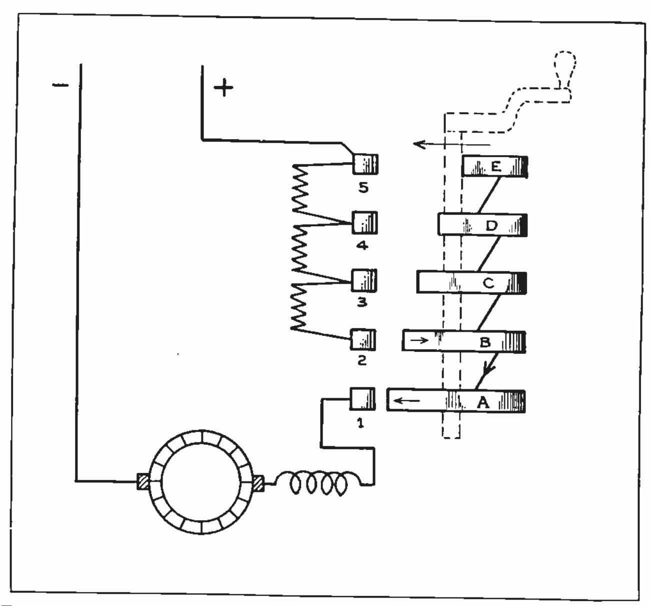

Fig. 135. Simple drum controller showing the method in which the contacts and segments cut out the armature resistance when starting the motor.

By making the resistance elements large enough to carry the motor current continuously, and the drum contacts and segments of heavy copper so they can stand the arcing and wear caused by opening and closing the motor armature circuit, this type of drum controller can be used for speed-regulating duty as well as for starting.

The motor used with this controller in Fig. 135 is a straight series motor similar to the type used on street cars and traction equipment.

175. REVERSING ROTATION OF MOTORS

We have learned that, in order **to reverse a D. C. motor, it is necessary to reverse either the field or the armature current, but not both.** Some controllers are connected to reverse the field of a motor, while others reverse the armature. On ordinary shunt motors the field is usually reversed, but with compound motors it is necessary to reverse both the shunt and series field if this method of reversing the motor is used.

So, for motors of this type, it is common practice to reverse the armature and leave both the shunt and series fields remain the same polarity. To reverse the armature leads will require only half as many extra contacts on the controller, as would be required to reverse both the series and shunt field leads.

When the direction of rotation of a compound motor is changed by reversing the field, both the series and shunt field leads should always be reversed; because if only one of these fields were reversed the motor would be changed from cumulative to differential compound.

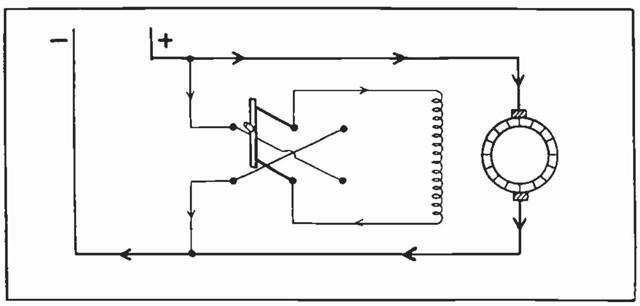

Fig. 136. The above sketch shows the manner in which a motor can be reversed by reversing its field with a double-pole, double-throw knife switch.

Fig. 136 shows the manner in which a simple double-pole, double-throw, knife switch can be used to reverse a shunt motor by reversing the connection between the field and the line.

When switch blades are closed to the left, current will flow through the shunt field in the direction shown by the arrows. If the switch is thrown to the right, the current will flow through the field in the opposite direction, as can readily be seen by tracing the circuit through the crossed wires between the stationary clips. This same switching method can, of course, be used to reverse the connections of the armature to the line, if desired. This reversing switch effect can be built into a drum controller by the proper arrangement of its contacts.

176. REVERSING DRUM SWITCHES

Fig. 137 shows a simple reversing drum-control used for reversing the direction of current through the armature only. This diagram doesn't show the starting resistance or contacts, but merely illustrates the principle or method by which several of the contacts on a drum controller can be used for a reversing switch.

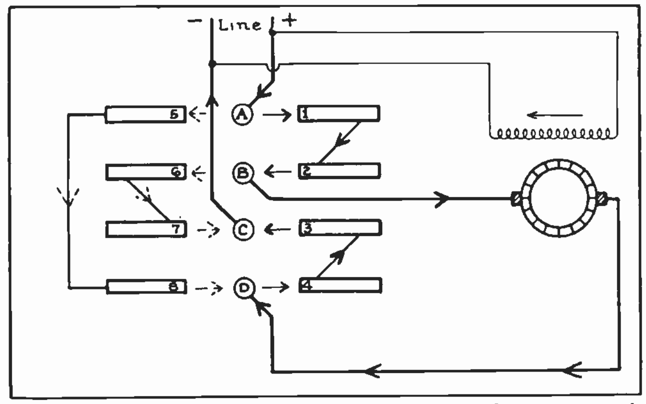

Fig. 137. Drum control with the contacts arranged to reverse the direction of current through the armature and thereby reverse the motor.

The drum control shown in Fig. 137 has one set of stationary contacts—A, B, C, and D, and two sets of moving segments or contacts, Nos. 1 to 8. These two sets of moving contacts are mounted on the same drum and both revolve at the same time, but in diagrams of this sort these parts are shown in a flat view in order to more easily trace the circuit.

If the drum contacts are moved to the left, the movable contacts 1, 2, 3, and 4, will be brought into connection with the stationary contacts A, B, C, and D. The current flow through the armature can then be traced by the solid arrows, from the positive line wire to stationary contact "A", movable segment 1, through the jumper to movable segment 2, stationary contact "B", through the armature in a right-hand direction, then to stationary contact "D," movable segment 4, through the jumper to movable segment 3, stationary contact "C"; and back to the negative line wire.

If the drum contacts are moved to the right the movable segments 5, 6, 7, and 8 will be brought into connection with the stationary contacts, and the armature current will then flow as shown by the dotted arrows. The field of the motor is left the same polarity and only the armature circuit is reversed. If the field and armature of a motor were both reversed at the same time, the direction of rotation would still remain the same.

177. REVERSING DRUM CONTROLLERS

Fig. 138 shows the circuit of a drum controller which is used for starting a D. C. motor, as well as for reversing duty. This controller has two sets of stationary contacts and two sets of movable segments. The diagram also shows the armature resistance used for starting the motor and while it is being brought up to speed. The contacts and parts of this drum are also laid out in a flat view in the diagram.

The two sets of movable segments are arranged on opposite sides of the drum, as are the stationary contacts. This is illustrated by the small sketch in the lower left-hand corner, which shows from a top view the position of the contacts at the time segments 1 to 5 are approaching the stationary contacts, "P" to "U".

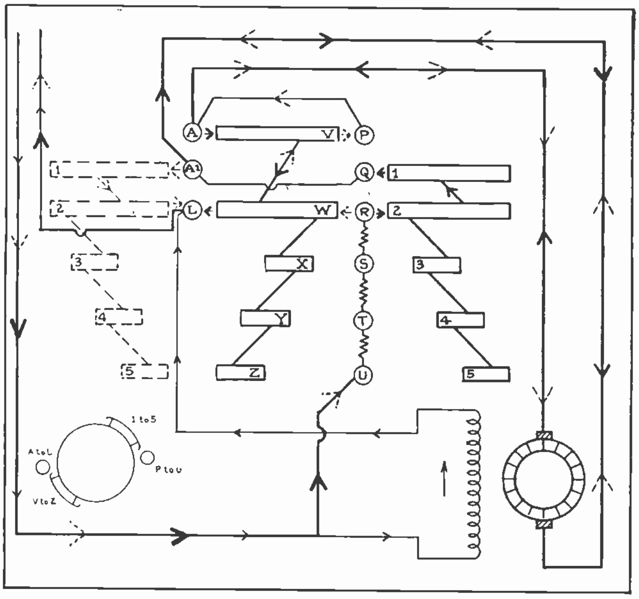

Fig. 138. Wiring diagram of a drum controller for starting and reversing shunt motors.

Now, suppose we move the drum of this controller so it will shift both sets of movable segments to the left in the flat diagram. The first step of this movement will bring movable segments 1 and 2 into connection with stationary contacts "Q" and "R", and will also bring segments "V" and "W" into connection with stationary contacts "A" and "L". A circuit can then be traced, as shown by the solid arrows, from the positive line wire to stationary contact "U", through all of the armature resistance to stationary contact "R", movable segment 2, through the jumper to movable segment 1, stationary contact Q to stationary contact A-1; then through the motor armature, back to stationary contact "A", movable segments "V" and "W", stationary contact "L", and back to the negative side of the line.

As we advance the controller still farther in this same direction, the successive steps will bring movable segments 3, 4 and 5 into connection with stationary contacts "S", "T", and "U", thus gradually shorting out the armature resistance step by step.

When the controller has been moved as far as it will go in this direction and all armature resistance has been cut out, the circuit is from the positive line wire to stationary contact "U", movable segment 5, through the jumpers and segments to movable segment 1, stationary contact Q, and on through the armature and back to the negative side of the line.

You will note that the movable segments 1 and 2, and "V" and "W" are all of sufficient length to remain in connection with the stationary contacts as they slide around and allow the step by step movement which brings the larger segments into connection with their stationary contacts.

To reverse the motor, we will now move the controller in the opposite direction, which will bring the movable segments 1 to 5 clear around on the opposite side to the position shown by the dotted segments, 1 to 5; and the movable segments "V" to "Z" will be brought into connection with stationary contacts "P" to "U".

Before attempting to trace the circuit, get well in mind the position of these movable segments in this new location. Another reference to the circular sketch in the lower corner of the figure will help you to see the manner in which the movable segments are brought up on the opposite side of the stationary contacts as the drum is revolved in the opposite direction.

We now find that, on the first step of the drum movement, the movable segments "V" and "W" will be brought into connection with the stationary contacts "P" and "R", and the movable segments 1 and 2 (dotted) will be brought into connection with stationary contacts "A-1" and "L".

We can now trace a circuit through the armature, as shown by the dotted arrows, from the positive line to stationary contact "U", through the full armature resistance to stationary contact "R", the movable segments "W" and "V", stationary contacts "P" and "A"; then through the armature in the opposite direction to what it formerly flowed, and back to stationary contact A-1; then through movable segments 1 and 2 to negative line terminal "L".

As the controller is advanced step by step in this direction, the movable segments "X", "Y", "Z" will cut out the armature resistance as the machine comes up to speed. In this position the movable segments 3, 4, and 5 will be idle.

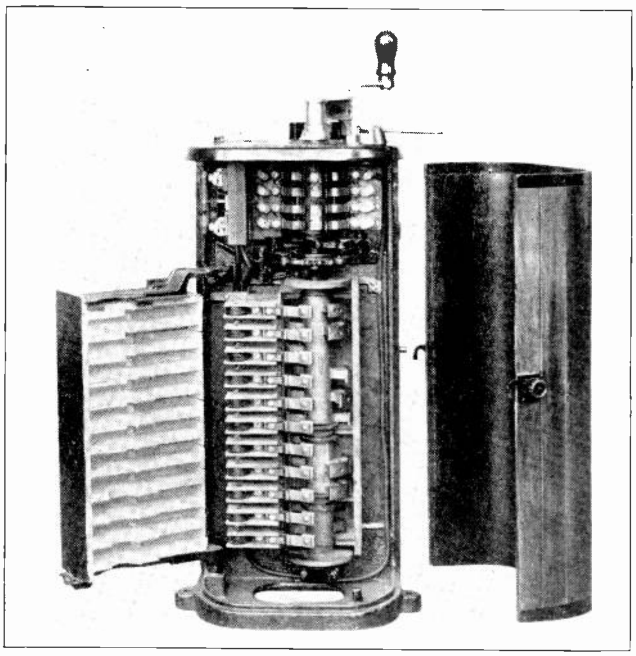

Fig. 139. The above photo shows the mechanical construction and arrangement of parts of a modern drum control. Note the flash barriers on the inner cover which is shown opened to the left.

The shunt field connections of this motor are left the same, so its polarity will remain the same at all times. Trace this diagram carefully until you are able to trace the circuit very readily in either direction or position of the control. A good knowledge of the principles and circuits of these controllers will be of great help to you in the selection of the proper controller for various applications in the field, and also in locating troubles which may occur in controllers of this type or the resistance attached to them.

178. CONSTRUCTION OF DRUM CONTROLS

Fig. 139 shows a photo of a drum controller with the cover removed so that all of the parts can be quite clearly seen. The movable segments are made of copper and are attached to the shaft or drum, which is operated by the crank or handle.

The stationary contacts are in the form of fingers with flat springs to hold them in good contact with the segments when they are passed under these fingers. You will note that the copper shoes of the rotating segments and the individual fingers or stationary contacts are both removable, so they can easily be replaced when they are worn or burned by arcing which occurs during the operation of the controller.

These contacts should always be kept in good condition in order to assure the proper operation of the motor to which the controller is attached. At the left of the stationary contact fingers, can be seen a row of blow-out coils all of which are in series with their respective contacts and circuits. These blow-out coils, as previously mentioned, are for the purpose of extinguishing the arc drawn when the circuits are broken at the contacts.

The inner hinged cover, which is shown swung out to the left, is simply an assembly of boards or barriers made of fireproof material. When this group of barriers is swung into place, one of them comes between each stationary contact and the next. The purpose of these barriers is to prevent a flash-over or short-circuit between adjacent contacts.

This particular drum controller has a separate set of reversing contacts mounted in the top of the case and operated by a separate small handle, which is shown at the right of the main crank.

In addition to the functions of starting, reversing, and varying the speed of motors, some controllers are also equipped with extra contacts for short circuiting the armature through a resistance, in order to provide what is known as **dynamic braking.**

This form of braking, which is frequently used to stop large motors, operates on the principle of a generator, using the counter-voltage generated in the armature to force a current load through the dynamic brake resistance. This method provides a very effective and smooth braking, and will be explained more fully in later paragraphs.

179. DRUM CONTROL FOR REVERSING AND SPEED REGULATING

Fig. 140 shows a diagram of a drum control which is arranged for starting, reversing, speed-regulating, and dynamic braking duty. This controller has two sets of heavy-duty segments and contacts for the armature circuit, and in the upper section are two

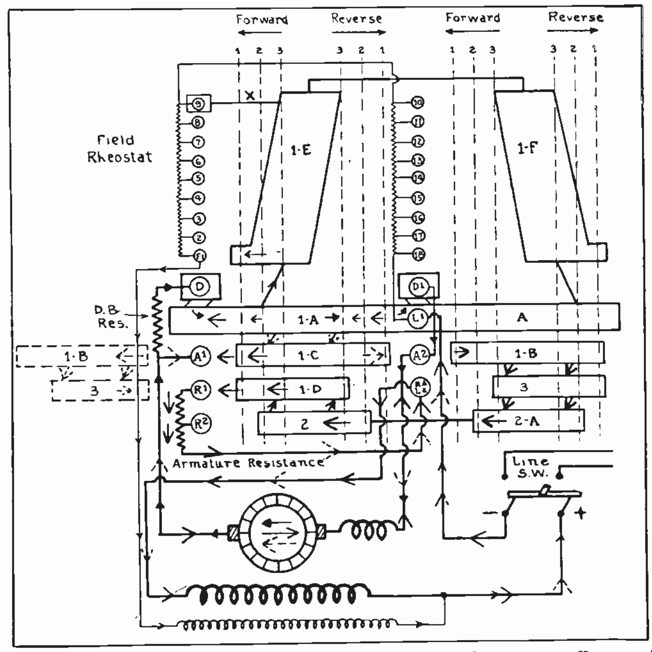

Fig. 140. This diagram shows the wiring for a drum controller used for starting, reversing, and varying the speed of a compound motor.

sets of smaller contacts which are used in the shunt field circuit, and are short circuited by two large angular segments.

The shunt field resistance, or rheostat, is shown divided into two sections in the diagram; but you will note that the taps made to this resistance run consecutively from No. 1 to 18, and the resistance itself can be located all in one group and have the separate leads brought to the two rows of contacts as shown. One of the heavy-duty resistances is used for the armature during starting, and the other is used for the dynamic braking.

When this controller is operated in either direction, the first step will close the armature circuit through the armature resistance, and energize the field at the same time, thus starting the motor. As the controller is advanced step by step, the armature resistance will first be cut out and then resistance will be cut in to the shunt field circuit, causing the motor to speed up as much more as desired.

When the controller is in idle position, as shown in the diagram, the motor armature is short circuited by the small movable segments which are now resting on the contacts "D" and "D-1". These contacts are the ones used for the operation of the dynamic brake circuit.

180. FORWARD POSITION, STARTING

The long movable segment "1-A" is continuous around the drum and always makes contact with "L-1". When the controller is moved to the left one step, the movable segment "1-B" connects with the stationary terminal "A-2" in the center of the diagram, and the segments "C" and "D" connect with stationary contacts "A-1" and "R-1" at the left of the diagram.

This completes a circuit through the motor armature and full armature resistance, as shown by the larger solid arrows. In tracing this circuit, remember that this first step of movement of the controller will remove the short segments from contacts "D" and "D-1", thus breaking the short circuit on the armature.

The armature circuit which has just been closed can be traced from the positve line wire to "L-1", to the left through segment "1-A", through the jumpers to segment "1-C", then to terminal "A-1", and through the armature in a right-hand direction, on to terminal "A-2", segment "1-B", through the jumpers and segments 3 and 2-A of the right-hand group, through jumpers and segments 2 and 1-D of the left group, then to contact "R-1", through all of the armature resistance, to the contact which is marked "R-3" and "L-2"; then through the series field winding and back to the negative side of the line.

This first step or movement of the controller also causes the approaching tip of the large angular segment "1-E" to connect to contact "F-1" and close a circuit directly through the shunt field of the motor, without any resistance in series. This circuit can be traced from the positive side of the line to contact "L-1", segment "1-A" up through jumper to segment "1-E", contact "F-1", and then through the shunt field winding and back to the line.

When the controller is advanced another step, segment 2 of the left group connects with contact "R-2", and cuts out the upper section of the armature resistance. When the controller is moved still another step, segment 3 of the right-hand group connects with the contact which is marked "R-3" and "L-2", and cuts out the entire armature resistance.

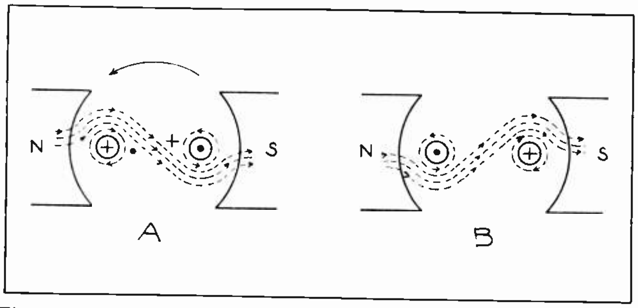

Fig. 141. The above sketch illustrates the principle of dynamic brake action in a motor when its armature is short circuited.

By checking the circuit again with the controller in this position, you will find that a circuit can be traced from the line through the controller and the motor armature, back to the line, without passing through the armature resistance.

The dotted lines which run vertically through the controller and are numbered 1, 2, 3 at their top ends, show which segments make connection with the stationary contacts on the first, second, and third steps of either the forward or reverse rotation of the controller.

For example, the dotted lines No. 1 in both forward groups touch only the segments which will connect with the stationary contacts on the first joint of the controller. The dotted lines No. 2 run through the segments which will connect with the stationary contacts on the second step of the controller. Etc. The dotted lines in the columns marked "reverse" show which segments make contact in order when the controller is moved in the reverse direction.

So far we have moved the controller only three steps to the left or in the forward direction, and we find that this has cut out all of the armature resistance and brought the motor up to approximately normal speed.

181. SPEED CONTROL

During these three steps or movements, the large angular segment "1-E" has been moving across contacts 1 to 9 of the shunt field resistance. These contacts are all shorted together by the segment "1-E", but this makes no difference, because they are not in the field circuit after the first step of the controller.

When the controller is moved the fourth step to the left, the lower end of segment "1-E" will have passed clear across the stationary contacts, and its lower right edge will begin to leave these contacts in the order —1, 2, 3, etc. This begins to cut in resistance in series with the shunt field winding of the motor, thus increasing the speed of the machine as much as desired.

During the time that segment "1-E" has been breaking away from contacts 1 to 9, the segment "1-F" has been moving across contacts 10 to 18; and after the upper right-hand corner, or segment "1-E", has cut in the last step of the resistance from 1 to 9, the segment "1-F" starts to cut in the resistance in the steps from 10 to 18. This gives a wide range of speed variation by means of the shunt field controller. The shunt field circuit is traced with the small solid arrows through the controller for the first position only.

182. REVERSE POSITION

To reverse the motor, the controller will be returned to neutral or "off" position, and then advance step by step in a right-hand direction. As the controller advances the first step in this direction, the right-hand ends of the movable segments will make connections with the groups of stationary contacts opposite to which they were connected before.

This means that segments "1-B" and 3 will have passed around the drum and will approach contacts "A-1" and "R-1" from the left, as shown by the dotted segments "1-B" and 3; and segments "1-C" and "1-D" will approach contacts "A-2" and "R-3" from the left.

With the controller in the first step of this reversed position, current can be traced through the armature by the dotted arrows, and we find it is in the reverse direction to what it formerly flowed through the motor armature.

This circuit is traced from the positive line wire to "L-1", segment "1-A", jumpers and segment "1-C" to contact "A-2", and then through the armature to the left, to contact "A-1", segments "1-B" and 3, contact "R-1", through the full armature starting resistance to contact "L-2"; then through the series field in the same direction as before and back to the negative line wire.

In tracing this circuit, we find that the direction of current through the armature has been reversed but that it remains the same through the series field winding. It is necessary to maintain the polarity of the series field the same in either direction of rotation, in order to keep the motor operating as a cumulative compound machine.

If the controller is advanced in the reverse direction, the additional steps will cut out the armature resistance and begin to insert resistance in the shunt field circuit, the same as it did in the former direction.

183. DYNAMIC BRAKING

When the controller shown in Fig. 140 is brought back to neutral or off position, we find that the short movable segments directly above the long segment "1-A" will be brought to rest on contacts "D" and "D-1", thus short-circuiting the motor armature through the dynamic braking resistance, contact "D", segment "1-A", contact "D-1", and the commutating field.

When the current is shut off from the motor armature by bringing the controller to the "off" position, if the motor is a large one or if the load attached to it has considerable momentum, the motor and machine or car which it is driving, will tend to keep on moving or coasting for some time before coming to a complete stop.

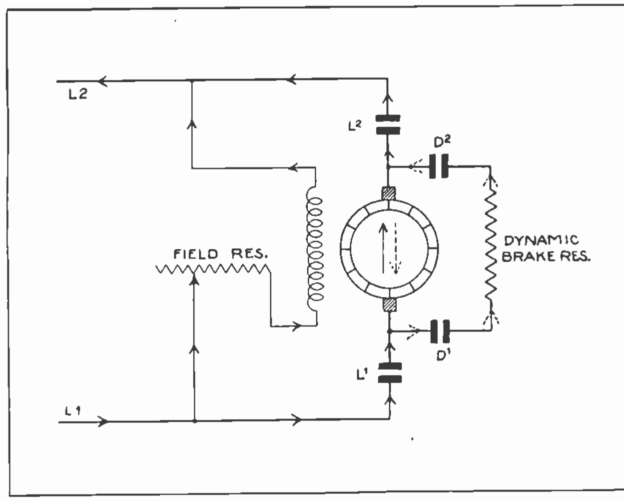

Fig. 142. Diagram showing connections and contacts used for switching a dynamic brake resistance across the armature of a D. C. motor when the line is disconnected.

If we leave the shunt field excited during this period, the motor armature will continue to generate its counter-voltage as long as it is turning. Then, if we short circuit the armature through the dynamic brake resistance, this counter-voltage will force a heavy load of current to flow and the coasting motor armature will act as a generator.

We know that it requires power to drive a generator armature; so, when this short or load is placed on the motor armature, the energy of its momentum is quickly absorbed by the generator action, thus bringing the armature to a smooth, quick stop.

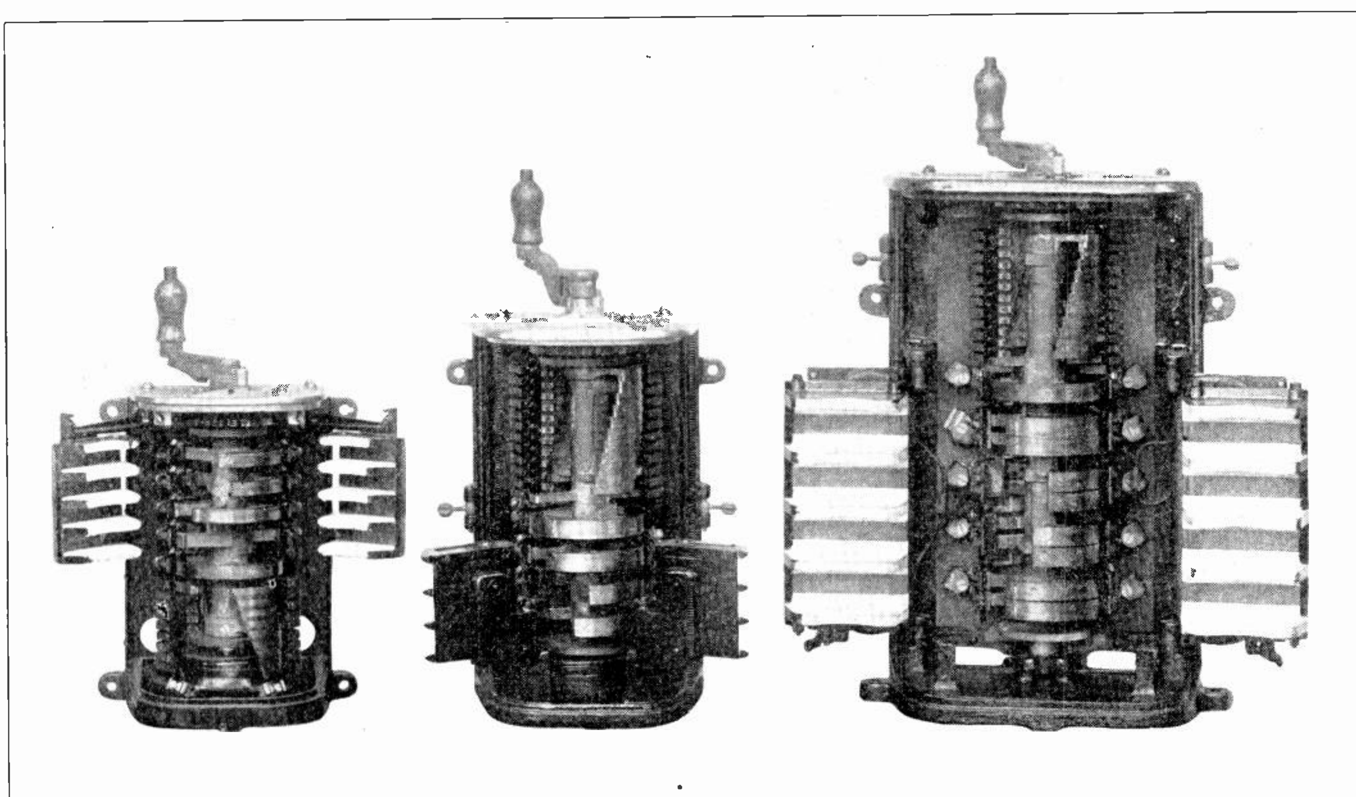

Fig 143. The above photo shows several types and sizes of modern drum controllers. Examine carefully the construction and arrangement of parts of each of these controls.

The field circuit is left complete when the controller is in the off position and as long as the line switch remains closed. This circuit can be traced from the positive line wire to contact "L-1", segment "1-A", segment "1-E", and the jumper at "X", segment "F D", contact 9 and through one-half of the shunt field resistance, then through the shunt field back to the negative line wire.

This half of the shunt field rheostat is left in series with the field for dynamic braking so that the motor armature will not generate too high a counter-voltage.

Another way of illustrating the effect of dynamic braking is as follows: You have learned that the counter-voltage is in the opposite direction to the applied line voltage which rotates the motor. Then, when we disconnect the armature from the line and connect it across the dynamic brake resistance, the armature continues to rotate in the same direction and will produce counter-voltage in the same direction; which will force current through the armature and braking resistance in the opposite direction to what the line current formerly flowed.

As this current resulting from counter-voltage is in the opposite direction to the normal armature current, it will tend to reverse the direction of the armature rotation. This is illustrated by the two diagrams in Fig. 141.

In the view at "A", the symbols marked within the conductors show the direction of the applied voltage and current during motor operation. The symbols marked at the side of the conductors illustrate the direction of the counter-voltage induced in them, which is opposite to the applied voltage and current. With the direction of the motor field as shown, the machine will normally rotate counter-clockwise.

In the view at "B", the line current has been shut off from the motor winding and the direction of current set up by counter-voltage through the armature winding and dynamic braking resistance is shown by the symbols within the conductors.

The polarity and direction of the motor field remain the same, but the direction of flux around the armature conductors is now reversed, and thus it tends to produce rotation in the opposite direction.

The effect of dynamic braking and the period of time in which the motor armature can be stopped by this method will depend upon the strength of field excitation which is left on the motor when the controller is placed in the off position, and upon the amount of resistance used for dynamic braking.

Fig. 142 shows a simplified connection diagram for a shunt motor equipped with dynamic braking. This diagram shows only the controlling contacts which would be used for dynamic braking alone. The solid arrows show the normal direction of current flow through the armature when it is operating from the line voltage, and with contacts "L-1" and "L-2" closed. During this time the contacts "D-1" and "D-2" are, of course, open.

When this motor is stopped, line contacts "L-1" and "L-2" are opened and contacts "D-1" and "D-2" are closed. The counter-voltage in the armature then sends current through it in the reverse direction, as shown by the dotted arrows.

The shunt field is connected across the line in series with its resistance and, as long as it remains excited, the current in the reverse direction will tend to reverse the rotation of the armature. As the motor armature slows down, the counter-voltage generated becomes less and less, and the effect of dynamic braking is reduced.

When the motor armature reaches a complete stop, the voltage in its conductors, of course, ceases to be generated. This results in a sort of cushioning effect and provides one of the smoothest forms of braking which can be used on D. C. motors.

184. REGENERATIVE BRAKING

In some cases, for example with railway motors, the principle of dynamic braking is used in what is known as **regenerative braking,** to actually feed current back to the line.

In order to accomplish this, it is necessary to leave the armature connected to the line and over-excite the field. Then, when an electric car or train, for example, starts down a grade and attempts to rotate its armature rapidly, the motor armature will generate a higher counter-voltage than the applied line voltage.

This will actually force current back into the line, as though this machine were operating in parallel with the power-plant generators.

Dynamic braking effects great savings in this manner and in some cases may supply from 10 to 35 per cent of the energy required by all trains on the system.

Dynamic braking on electric railway applications also saves an enormous amount of wear on brake shoes and air-brake equipment, and a great amount of wear and tear in cases where it is used for cranes, hoists, etc.

Neither dynamic braking nor regenerative braking is effective when the machine is at a stop or practically stopped. Therefore, it is necessary to have either mechanical or magnetic brakes to hold the motor armature stationary if there is some load which tends to revolve it, such as the load on a crane or elevator motor, or the tendency of a train to run down a grade.

Fig. 143 shows three drum controllers of different sizes and types. Note the various arrangements of contacts which can be provided to obtain different control features on the motors.

CARBON BRUSHES

The brushes play a very important part in the operation of any D. C. motor or generator, and are well worth a little special attention and study in this section.

The purpose of the brushes, as we already know, is to provide a sliding contact with the commutator and to convey the current from a generator armature to the line, or from the line to a motor armature, as the case may be. We should also keep in mind that the type of brush used can have a great effect on the wear on commutators and in producing good or bad commutation.

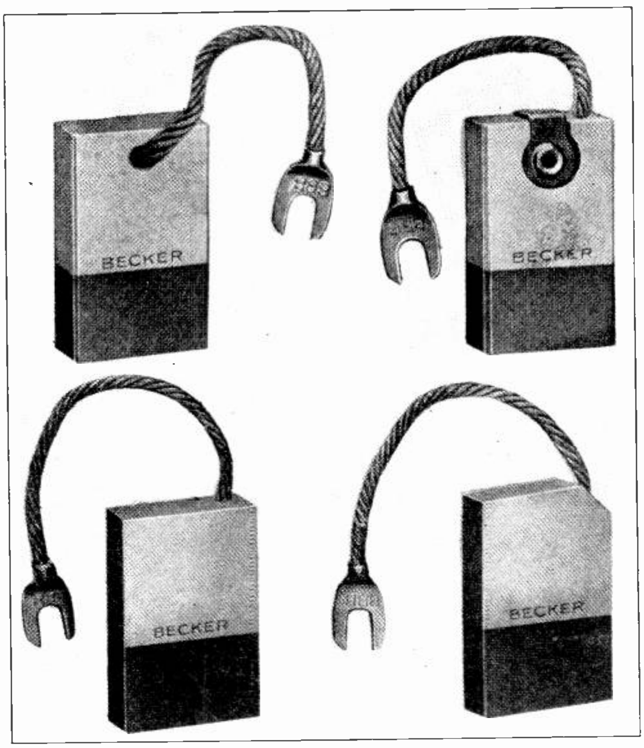

Fig. 144. Above are shown several carbon brushes of common types, such as used on D. C. motors and generators.

It should not be assumed, just because any brush will carry current, that any piece of carbon or any type of brush will do for the replacement of worn brushes on a D. C. generator or motor. This is too often done by untrained maintenance men, and it frequently results in poor commutation and sometimes serious damage to commutators and machines.

Many different grades of brushes are made for use on machines of various voltages and commutator speeds and with different current loads.

In order to avoid sparking, heating, and possible damage to commutators, it is very important when replacing worn brushes to select the same type of brushes or brush materials as those which are removed.

In special cases it is necessary to use only the brushes made by the manufacturers of certain motors or generators for those particular types of machines. Or, in difficult cases of brush or commutator trouble, it may be necessary to have a specialist from a brush manufacturing company determine exactly the type of brush needed. But in the great majority of cases you can replace brushes very satisfactorily by applying the principles and instructions given in the following paragraphs.

185. BRUSH REQUIREMENTS

A good brush should be of low enough resistance lengthwise and of great enough cross-sectional area to carry the load current of the machine without excessive heating. The brush should also be of high enough resistance at the face or contact with the commutator to keep down excessive currents due to shorting the armature coils during commutation. In addition, the brush should have just enough abrasive property to keep the surface of the commutator bright and the mica worn down, but not enough to cut or wear the commutator surface unnecessarily fast.

Figs. 144 and 145 show several carbon brushes of different shapes, with the "pigtail" connections used for carrying the current to the brush-holder studs.

186. BRUSH MATERIALS

The most commonly used brushes are made of powdered carbon and graphite, mixed with tarry pitch for a binder, and molded under high pressure into the shapes desired. This material can be molded into brushes of a certain size, or into blocks of a standard size from which the brushes can be cut.

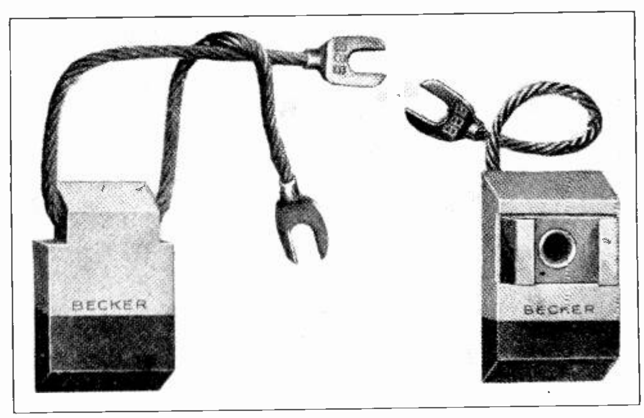

Fig. 145. Two carbon brushes of slightly different shapes, such as used with reaction type brush holders.

The molded material is then baked at high temperatures to give it the proper strength and hardness and to bake out the pitch and volatile matter.

Carbon is a very good brush material because it is of low enough resistance to carry the load currents without too great losses, and yet its resistance is high enough to limit the short circuit currents between commutator bars to a fairly low value. Carbon also possesses sufficient abrasiveness to keep commutator mica cut down as the commutator wears.

Graphite mixed with carbon in the brushes provides a sort of lubricant to reduce friction with the commutator surface. It also provides a brush of lower contact resistance and lower general resistance, and one with greater current capacity.

Powdered copper is sometimes added or mixed with graphite to produce brushes of very high current capacity and very low resistance. These brushes are used on low-voltage machines such as automobile starting motors, electro-plating generators, etc. They often contain from 30 to 80 per cent of copper, and such brushes will carry from 75 to 200 amperes per sq. in.

Lamp-black is added to some brushes to increase their resistance for special brushes on high-voltage machines.

187. COMMON BRUSH MATERIAL. BRUSH RESISTANCE

A very common grade of carbon-graphite brush is made of 60% coke carbon and 40% graphite, and is known as the "utility grade". Brush material of this grade can be purchased in standard blocks 4" wide and 9" long, and in various thicknesses.

Brushes for repairs and replacement can then be cut from these blocks. **They should always be cut so that the thickness of the block forms the thickness of the brush,** as the resistance per inch through these blocks is higher from side to side than it is from end to end or edge to edge. This is due to the manner in which the brush material is molded and the way the molding pressure is applied, so that it forms a sort of layer effect or "grain" in the carbon particles.

This higher "cross resistance" or lateral resistance is a decided advantage if the brushes are properly cut to utilize it, as it helps to reduce short-circuit currents between commutator bars when they are shorted by the end of the brush.

Fig. 146 shows how brush measurements should be taken and illustrates why it is an advantage to have the highest resistance through the thickness of the brush and in the circuit between the shorted commutator bars.

The resistance of ordinary carbon-graphite brushes usually ranges .001 to .002 ohms per cubic inch, and these brushes can be allowed to carry from 30 to 50 amperes per sq. in. of brush contact area.

These brushes can be used on ordinary 110, 220, and 440-volt D.C. motors; and on small, medium, and large sized generators which have either flush or undercut mica, and commutator surface speeds of not over 4000 feet per min.

188. HARDER BRUSHES FOR SEVERE SERVICE

These utility grade carbon-graphite brushes can be obtained in a harder grade, produced by special processing, and suitable for use on machines which get more severe service and require slightly more abrasiveness. These harder brushes are used for steel mill motors, crane motors, elevator motors, mine and mine locomotive motors, etc.

Brushes with a higher percentage of carbon can be used where necessary to cut down high mica, and on machines up to 500 volts and with commutator speeds not over 2500 feet per minute. This type of brush is usually not allowed to carry over 35 amperes per square inch, and is generally used on machines under 10 h. p. in size.

189. GRAPHITE USED TO INCREASE CURRENT CAPACITY

Brushes of higher graphite content are used where high mica is not encountered, and for heavier current capacity. Such brushes are generally used only on machines which have the mica undercut; and are particularly adapted for use on older types of generators and motors, exhaust fans, vacuum cleaners, washing machines, and drill motors.

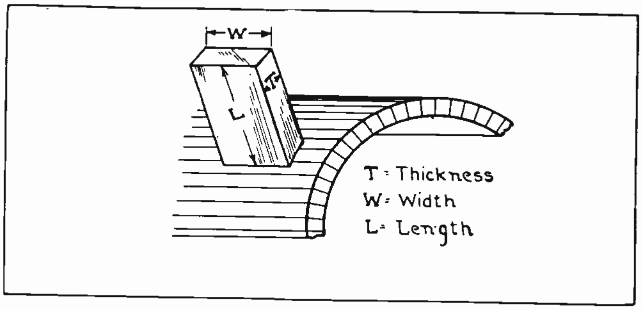

Fig. 146. This sketch illustrates the method of taking measurement for the length, width, and thickness of carbon brushes.

Brushes with the higher percentage of graphite do not wear or cut the commutators much, but they usually provide a highly-polished surface on both the commutator and brush face. After a period of operation with these brushes the surface of the commutator will usually take on a sort of brown or chocolate-colored glaze which is very desirable for long wear and good commutation.

190. SPECIAL BRUSHES

Some brushes are made of practically pure graphite and have very low contact resistance and high current-carrying capacity. Brushes of this nature will carry from 60 to 75 amperes per square inch and they can be used very satisfactorily on machines of 110 and 220 volts, or on high-speed slip rings with speeds even as high as 10,000 feet per minute.

The greater amount of graphite offers the necessary lubrication properties to keep down friction at this high speed.

Another type of brush consisting of graphite and lamp-black, and known as the electro-graphitic brush, is made for use with high-voltage machines which have very high commutator speeds. These brushes have very high contact resistance, which promotes good commutation. They can be used to carry up to 35 amperes per square inch and on commutators with surface speeds of 3000 to 5000 feet per minute.

These brushes are made in several grades, according to their hardness; the harder ones are well adapted for use on high-speed fan motors, vacuum cleaners, drill motors with soft mica, D. C. generators, industrial motors, and the D. C. side of rotary converters. They are also used for street railway motors and automobile generators, and those of a special grade are used for high-speed turbine-driven generators and high-speed converters.

191. BRUSH PRESSURE OR TENSION

It is very important to keep the springs of brush holders or brush hammers properly adjusted so they will apply an even amount of pressure on all brushes. If the pressure is higher on one brush than on another, the brush with the higher pressure makes the best contact to the commutator surface and will carry more than its share of the current. This will probably cause that brush to become overheated.

To remedy this, the spring tension should be increased on the brushes which are operating cool, until they carry their share of the load.

Brush pressure should usually be from 1¼ to 3 lbs. per square inch of brush contact surface. This brush tension can be tested and adjusted by the use of a small spring scale attached to the end of the brush spring or hammer, directly over the top of the brush. Then adjust the brush holder spring until it requires the right amount of pull on the scale to lift the spring or hammer from the head of the brush. One can usually tell merely by lifting the brushes by hand, whether or not there are some brushes with very light tension and others with too heavy tension or pressure.

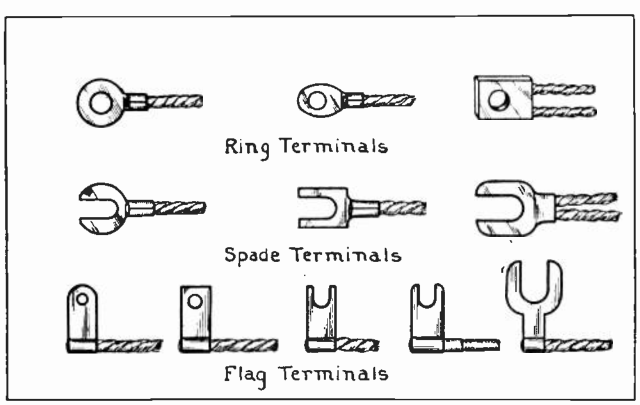

Fig. 147. Above are shown several types of terminals for brush shunts or leads.

Motors used on street cars, trucks, and moving vehicles, or in places where they are subject to severe vibration, will usually require a higher brush-pressure to keep the brushes well seated. On such motors the pressure required may even range as high as 4 lbs. per square inch.

192. BRUSH LEADS OR SHUNTS

All brushes should be provided with flexible copper leads, which are often called "pigtails" or brush shunts. These leads should be securely connected to the brushes and also to the terminal screws or bolts on the brush holders, and their purpose is to provide a low-resistance path to carry the current from the brush to the holder studs.

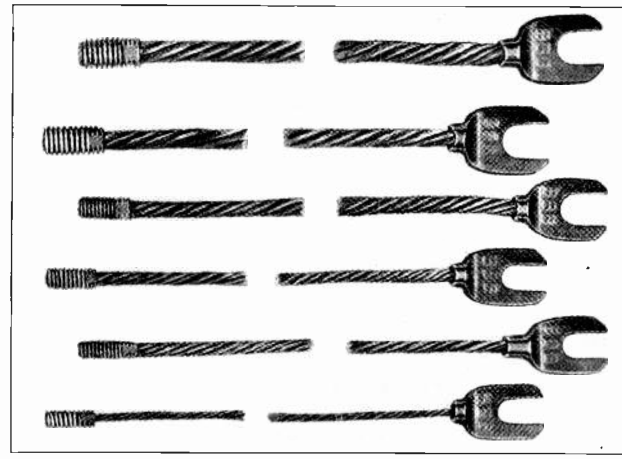

Fig. 148. Brush shunts can be obtained with threaded plugs on their ends for securely attaching them to the brushes.

If these brush shunts or leads become loose or broken, the current will then have to flow from the brush through the holder or brush hammers and springs. This will often cause arcing that will damage the brush and holder and, in many cases, will overheat the springs so that they become softened and weakened and don't apply the proper tension on the brushes.

The brushes shown in Figs. 144 and 145 are equipped with leads or brush shunts of this type and Fig. 147 shows a number of the types of copper terminals or clips that are used to attach these leads to the brush holders by means of terminal screws or bolts.

When new brushes are cut from standard blocks of brush material, the pigtails can be attached by drilling a hole in the brush and either screwing the end of the pigtail into threads in this hole or packing the strands of wire in the hole with a special contact cement.

Fig. 148 shows a number of brush shunts or leads with threaded plugs attached to them. These leads can be purchased in different sizes already equipped with threaded end plugs.

Fig. 148 illustrates the method of preparing a brush and inserting the threaded ends of the brush shunts. The top view shows a bar of brush stock from which the brushes may be cut, and in the center is shown the manner of drilling a hole in the corner of the brush.

Carbon graphite brushes are soft enough to be drilled easily with an ordinary metal drill, and they are then tapped with a hand tap, as shown in the left view in Fig. 148. The threaded plug on the end of the copper lead can then be screwed into this hole in the brush by means of pliers, as shown in the lower right-hand view of the same figure.

Brush leads of this type save considerable time in preparing new brushes, and insure a good low resistance connection to the brush. These leads can be unscrewed and removed from worn brushes, and used over a number of times.

193. CEMENT FOR ATTACHING LEADS TO BRUSHES

When brush leads with threaded tips are not available, a special compound or cement can be made by mixing powdered bronze and mercury. The bronze powder should first be soaked in muriatic or hydrochloric acid, to thoroughly clean it.

The acid should then be washed from the powder with lukewarm water. The bronze powder can then be mixed with mercury to form a thick paste. This paste is tamped solidly around the copper strands of the brush lead in the hole in the carbon brush, and will very soon harden and make a secure connection of low resistance.

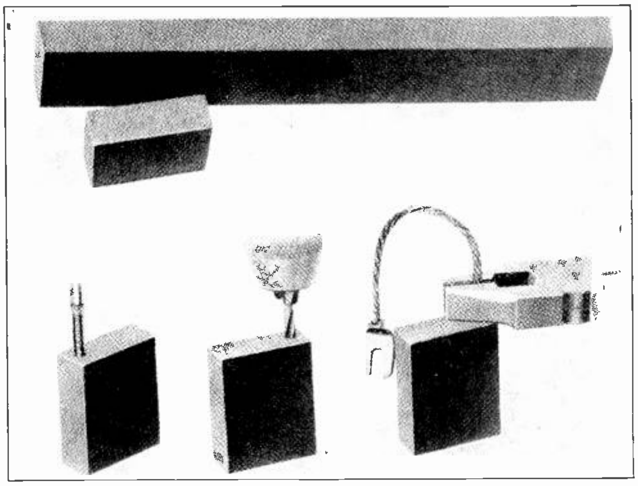

Fig. 148-A. These views illustrate the method of preparing a carbon brush to attach the threaded end of the brush lead or pigtail.

Care must be used not to make this cement too thick or it may harden before it can be tamped in place. It is usually advisable to mix only a very small quantity of the paste at one time, because it may require a little experimenting to get it just the right consistency.

194. DUPLICATING AND ORDERING BRUSHES

Worn or broken brushes should always be promptly replaced, before they cause severe sparking and damage to the commutator. Always replace brushes with others of the same grade of material if possible. The new brushes should also be carefully cut to the same size, so they will span just the same width on the commutator bar and will not fit too tight or too loose in the holders.

If it is necessary in emergencies to replace one or more brushes with others of a slightly different grade, place all those of one grade in the positive brush holders, and those of the other grade in the negative holders. If brushes of different grades are placed in the same set of holders, the current will divide unequally through them and cause heating of certain ones, and it may also cause unequal wear on the commutator.

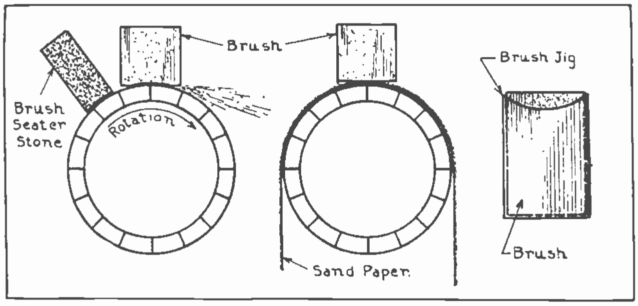

Fig. 149. The above sketches show several methods of cutting brush faces to fit the commutator surface. Each is explained in the accompanying paragraphs.

When ordering new brushes for any certain machine, careful measurements should be taken of the brush width, thickness, and length. The brush thickness is measured in the direction of travel of the commutator or slip rings; the width is measured parallel to the armature shaft or commutator bars; and the length is measured perpendicularly to the commutator or slip ring surface. These measurements are shown in Fig. 146. Any other special measurements should also be given, and in some cases it is well to send the old brush as a sample.

The length of brush leads or shunts should also be specified when ordering new brushes. They are usually provided in standard lengths of five inches, but can be furnished shorter or longer where required.

The style of terminal or end-clip should also be given, along with the diameter of the slot or hole by which they are attached to the bolts on the brush-holder studs.

It is generally advisable to have on hand a few of the brushes most commonly required for re-

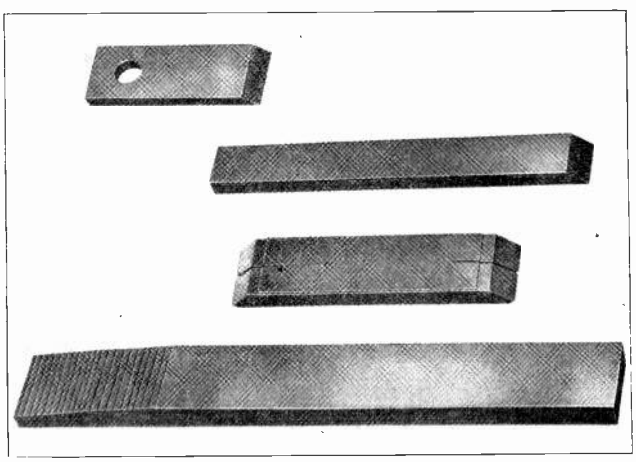

Fig. 150. Brushes made of copper strips or copper "leaf" construction are often used for low voltage machines which handle very heavy currents.

placement on any machines you may be maintaining. It is also well to have a catalogue of some reliable brush manufacturer, to simplify ordering by giving the number and exact specifications of the brushes required.

195. FITTING NEW BRUSHES TO THE COMMUTATOR

New brushes should always be carefully fitted to the surface or curvature of the commutator. This can be done by setting the brush in the holder with the spring tension applied, and then drawing a piece of sandpaper under the contact surface or face of the brush, as shown in the center view in Fig. 149. **Never use emery cloth for fitting brushes, as the electrical conducting of the emery particles tends to short circuit the commutator bars.**

The sandpaper should be laid on the commutator with the smooth side next to the bars and the rough or sanded side against the face of the brush. Then, with the brush held against the paper by the brush spring, draw the paper back and forth until the face of the brush is cut to the same shape as the commutator surface.

Be sure to hold the ends of the sandpaper down along the commutator surface so these ends will not cut the edges of the brush up away from the commutator bars.

On small machines where it is difficult to use sandpaper in the manner just described, a **brush-seater stone** can be used. These stones consist of fine sand pressed in block or stick form with a cement binder.

The brush seater is held against the surface of the commutator in front of the brush, as shown on the left in Fig. 149, and as the commutator revolves it wears off sharp particles of sand and carries them under the brush, thus cutting out the end of the brush until it fits the commutator.

When fitting a number of brushes, a brush jig such as shown on the right in Fig. 149 can be used to save considerable time. This jig can be made of either metal or wood, and in the form of a box into which the brush will fit. The open end of the box or jig has its sides cut to the same curve as the commutator surface.

A new brush can then be dropped in this box and its face cut out to the curve or edge of the box by means of a file. The bulk of the carbon can be cut out very quickly in this manner, and the brush can then be set in the holder and given a little final shaping with sandpaper as previously explained.

Graphite brushes should generally be used on iron slip rings on three-wire generators, and metal-graphite brushes on copper rings.

On certain very low voltage machines where heavy currents are handled, "copper leaf" brushes are used. These are made of a number of thin flat strips of hard drawn copper, with the end of the group beveled as shown in Fig. 150.

When brushes of too low resistance are used, they will generally cause long, yellow, trailing sparks at the commutator surface behind the brushes.

Brushes of too high resistance will cause blue sparks and will also cause the brushes to overheat.

If the commutator mica is not being cut down by the brushes and becomes too high, it will cause sparking and burned spaces to the rear of the mica segments, on the leading edges of the commutator bars.

The proper type of brushes and their proper fitting, well deserve thorough attention on the part of any electrical maintenance man or power plant operator; as a great many troubles in motors and generators can be prevented or cured by intelligent selection and care of brushes.

MAINTENANCE OF D. C. MACHINES

Direct current motors and generators are so similar to each other in mechanical construction and electric operation that many of the same rules for care and maintenance apply to both.

With the many thousands of these machines in use in factories, mines, power plants, steel mills, stores, and office buildings, and on railways, the electrician who can intelligently and efficiently operate and maintain them is in great demand.

Most of the repairs and adjustments which have to be made on D. C. machines are usually on parts that are easily accessible and which can be easily handled with simple tools.

In the majority of cases, the brushes, commutator, and bearings require closer attention and more frequent repair than other parts of the machines. These should not, however, require an excessive amount of attention if the motors or generators are operating under favorable conditions and are given the proper care.

The windings of motors and generators very seldom give any trouble, unless the machines are frequently overloaded or if the windings are very old or are subjected to oil and dirt.

196. IMPORTANCE OF CLEANING

One of the most important rules for the maintenance of all electric machines is **to keep them clean and well lubricated.** If this simple rule is followed it will prevent a great many of the common troubles and interruptions to the operation of the equipment.

If dust and dirt are allowed to accumulate in the windings of motors or generators, they clog the ventilation spaces and shut off the air which is necessary for proper cooling of the machine. A layer of dust is also an excellent insulator of heat, and tends to confine the heat to the windings and prevent its escape to the surrounding air. Dust and dirt also absorb and accumulate oil and moisture.

For these reasons, the windings of all electric machines should be kept well cleaned by brushing them with a duster or cloth and occasionally blowing out the dust from the small crevices by means of a hand-bellows or low pressure compressed air. Never use compressed air of over 40 lbs. pressure per square inch, or air that contains particles of grit or metal or any moisture.

Sometimes it is necessary to wash off an accumulation of oily or greasy dirt from the windings of machines. This can be done with a cloth and gasoline. If the windings are well impregnated with insulating compound, the gasoline will not penetrate deeply into them, but if it is allowed to soak into the windings to any extent they should be thoroughly dried before the machine is again connected to a line or operated.

A mixture of from ¼ to ½ of carbon-tetra-chloride with gasoline reduces the danger of fire or explosion when using it as a cleaning solution.

197. EXCESSIVE OIL VERY DETRIMENTAL TO ELECTRIC MACHINES

Oil is very detrimental and damaging to the insulation of machine windings and should never be allowed to remain on them. Once a winding becomes thoroughly oil-soaked, it will probably have to be rewound.

In some cases, if the oil has not penetrated too deeply, it may be possible to wash it out with gasoline and then thoroughly dry out the gasoline before the winding is put back in service.

When oiling the bearings of a motor or generator, extreme care should be used not to fill the oil-cups or wells too full and cause oil to run over on to the commutator or windings of the machine.

It is practically impossible to secure good commutation if the commutator of a motor or generator is covered with dirt and oil. This will cause the faces of the brushes to become glazed and packed with dirt and will in many cases cause considerable sparking.

Dirt and oil will form a high-resistance film on the surface of the commutator, which will tend to insulate the brushes and prevent them from making good contact.

Oil is also very damaging to the cement used in the mica segments of commutators.

If any oil accidentally gets on the surface of a commutator, it should be wiped off immediately with a cloth and a small amount of kerosene or gasoline and carbon-tetra-chloride. **Gasoline should not be used around a running machine because of the danger of igniting it by a spark from the brushes.**

198. KEEP BEARINGS WELL LUBRICATED

The bearings of all motors and generators should be kept well oiled but not flooded with oil. The oil in the bearings should be examined frequently to make sure that it is clean and free from dirt and grit, and should be changed whenever necessary.

If the oil in a bearing has become exceptionally dirty or mixed with any abrasive dirt, the oil should be drained and the bearing and oil-cup washed out with kerosene or gasoline. The bearing and cup should then be refilled with clean fresh oil and when the machine is started it should be revolved slowly at first, to be sure that all the kerosene or gasoline on the bearing surfaces has been replaced by oil before the machine is running at full speed.

Bearings should not be filled from the top when regular oil openings or vents are provided on the side.

Bearings which are equipped with oil rings should be inspected frequently to make sure that the rings are turning and supplying oil to the shaft. Check the temperature of bearings frequently either by means of a thermometer, or by feeling of them with the hand to make sure that they are not operating much above normal temperature.

A great amount of work and trouble and costly shut-downs of electrical machinery can be prevented by proper attention to lubrication of bearings.

199. WINDING TEMPERATURES

The temperature of machine windings should be frequently checked to see that they are not operating too hot, that is at temperatures higher than 40° C. above that of the surrounding air.

Convenient thermometers can be obtained for this use and placed in crevices in the winding or against the side of the winding with a small wad of putty pressed around the thermometer bulb and against the winding.

All terminals and connections on electric machines should be frequently inspected and kept

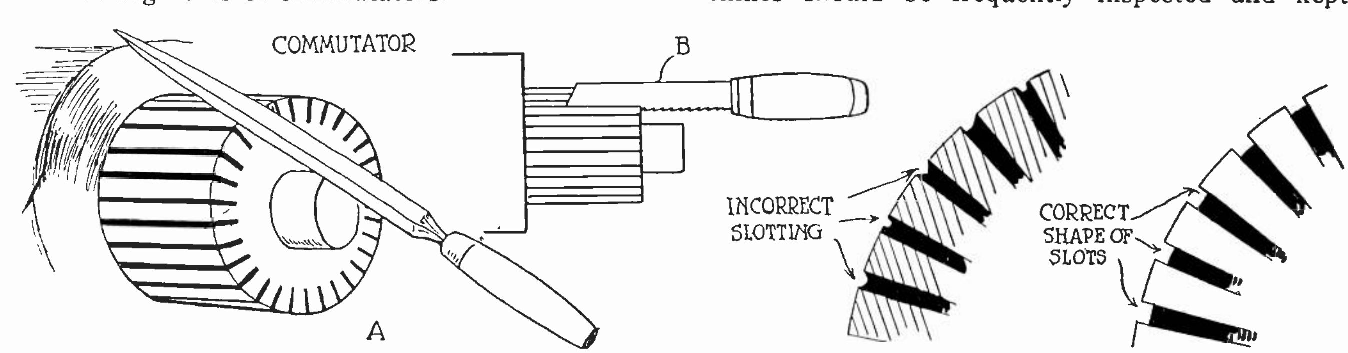

Fig. 151. The above sketch shows methods of undercutting mica segments on the commutator. Mica must be kept down even with, or below the surface of the commutator bars, or it will cause the brushes to make poor contact and cause severe sparking.

securely tightened. This includes those at the line, at the controller or starting switches, and at the brushes and field coils.

200. PROTECT MACHINES FROM WATER

Moisture or water is always a menace to the insulation and operation of electrical machinery, and machines should be thoroughly protected to keep all water away from their windings and commutators. If a motor or generator is located where water from above may drip upon the commutator, it is very likely to cause flash-overs and damage to the brushes and commutator.

If the windings of a machine become water-soaked or damp, they must be thoroughly dried, either by baking in an oven or by passing low-voltage direct current through the machine to dry them out.

Where a machine is too large to put in an oven or where no oven is available, the armature can be locked to prevent its rotation and then, by the use of a rheostat, low-voltage direct current can be applied in just the right amount to dry out the winding.

Water should be carefully excluded from oil wells and bearings, as it is not a good lubricant and it may cause serious damage if it mixes with the oil.

Motors that operate pumps may often have to be enclosed in a special box or shielding to prevent any drip or spray from coming in contact with them.

201. BRUSH ADJUSTMENT AND MICA UNDERCUTTING

Brushes should be frequently inspected to see that they are seated properly on the commutator and have the proper spring tension. If the commutator mica becomes high it should be corrected, either by using brushes of a type that will keep the mica cut down, or by undercutting the mica with a tool for this purpose.

Commutator mica on small machines can be undercut by hand with a piece of hack-saw blade equipped with a handle, as shown in Fig. 151. The views on the right in this figure show the correct and incorrect methods of undercutting mica.

Mica should be cut squarely with smooth, easy strokes of the hack-saw blade held in a vertical position. The mica should not be cut away too deeply, or the grooves will tend to accumulate dust and dirt, and cause short circuits between the commutator bars.

On small and medium-sized machines, the undercutting need not to be deeper than from $\frac{1}{64}$ to $\frac{1}{32}$ of an inch. Care should be taken not to scratch or scar the commutator bars while undercutting mica, and one should also be careful not to leave on the edges or corners of the bars any burrs which might cause a short circuit between them.

A small, three-cornered file can be used for cleaning the ends or corners of the mica segments, as shown in the left view in Fig. 151, but a file or three-cornered object should not be used for undercutting mica, as the top of the mica segments must be cut squarely, as shown in the right-hand view in the figure.

For undercutting the mica on large machines, a regular motor-driven mica cutter can be used. These machines consist of a small rotary saw, driven by a motor with a flexible shaft and equipped with handles for guiding the saw blade in the mica slots.

202. RESURFACING AND TRUING OF COMMUTATORS

If the surface of the commutator becomes rough and pitted it can be cleaned with sandpaper. Small spots of dirt or very lightly burned spots may be removed by holding sandpaper against the commutator while the machine is running.

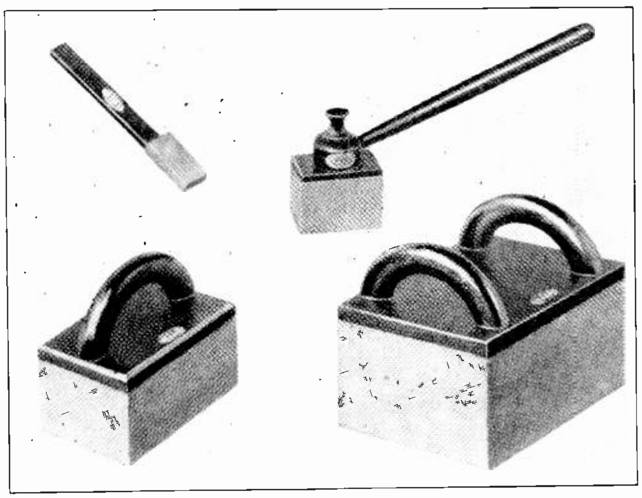

Fig. 152. Commutator stones of the above types are used for dressing or grinding down the burned and rough spots on commutator surfaces.

If the commutator requires much sand-papering it should be done with a block, with a curved surface to fit the commutator, to hold the sandpaper in a manner that will tend to smooth out hollow spots or high spots on the bars, and bring the commutator back to a true round shape.

Several strips of sandpaper can be folded over the curved end of a block of this type and fastened in place with clamps or tacks. As each strip becomes worn it can be removed, exposing the next strip, etc.

Special commutator stones can be obtained for dressing or re-surfacing commutators. These stones consist of a block of grinding or abrasive material equipped with handles for convenient application to the commutator surface. Several stones of this type are shown in Fig. 152. These can be obtained in different sizes and degrees of hardness for use with machines having commutators of different diameters and surface speeds.

If a commutator has become badly pitted or burned or out of round, it may be necessary to remove the armature from the machine and turn the commutator down in a lathe, as shown in Fig. 154. When truing a commutator in a lathe one should never remove any more copper than is absolutely necessary, because even a very light cut with a lathe

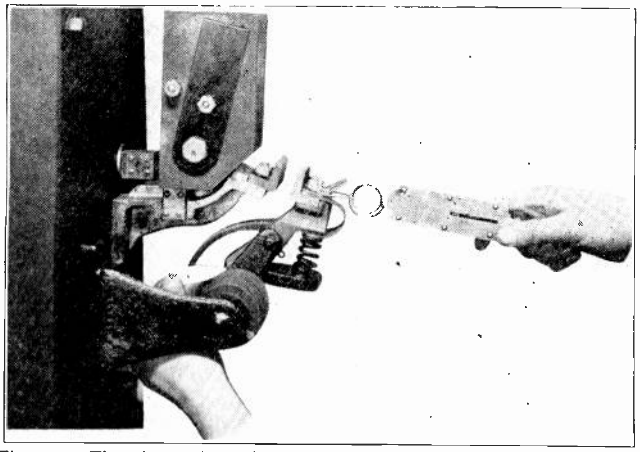

Fig. 153. The above photo illustrates the method of testing the contact pressure or tension of controller contacts. The scale can be used in the same manner for adjusting tension on brushes.

tool will remove more copper from the bars than several years of ordinary wear would destroy.

The armature should be carefully centered to run true in the lathe, and the tool set to remove only a very thin coating of copper, no thicker than a thin piece of paper. If this first cutting doesn't remove the flat spots, another cut can be made.

Commutators should never be turned down except as a last resort or when they are badly out of round.

Special tools and tool holders are often used for turning large commutators right in the machine.

Motors and generators should always have secure and firm foundations and should be anchored so that they don't vibrate while running. If the machine is allowed to vibrate, it may cause serious damage to the bearings and possibly also damage the commutator, shaft, or windings.

203. CARE OF CONTROLLERS

All switches, circuit breakers, and controllers used in connection with motors and generators should be kept in good condition, because if they are allowed to become defective, they may cause damage to the machines by frequent interruptions in the current supply, or by causing voltage drop and lower voltage than the machine is supposed to operate on, or by failure to protect the machine in case of overload.

All contact shoes or fingers on starting and control equipment should be kept in good condition and securely tightened. Bolts, nuts, screws, and terminals should also be kept tight and clean.

Sliding contacts or make-and-break contacts of controllers should be kept properly lubricated to prevent excessive wear. A good grade of vaseline serves very well for this purpose, as it will remain where applied on the contacts and will not run or spread over the equipment.

Resistance elements of starting and control equipment should be kept in good condition. In case of open circuits in resistance units, it may be necessary to temporarily bridge this open section of the resistance with a shunt or jumper, in order to keep the machine in operation; but the defective resistance unit should be replaced with a new one as quickly as possible to prevent overloading the machine when starting, due to having insufficient resistance in the armature circuit.

Dash pots and time element devices should be kept properly adjusted to allow the proper time for starting of motors.

204. CARE OF OVERLOAD PROTECTIVE DEVICES

Fuses and overload devices on control equipment or anywhere in the circuit to electrical machines should be kept in good condition, and should be of the proper size and adjustment to protect the machines from current overloads. Fuses should never be replaced with others of larger current ratings than the machines are supposed to carry.

Overload trip coils on circuit breakers should be kept properly adjusted to trip at any current above the normal percentage of overload which the machine is allowed to carry.

If breakers or fuses open frequently in the circuit, it is an indication of some overload or fault on the machines, and the trouble should be located and remedied, instead of setting the circuit breakers for heavier currents or using larger fuses.

205. LIST OF COMMON TROUBLES

In the following lists are given a number of the more common troubles of D. C. machines and the symptoms which indicate these troubles:

MOTORS

MOTOR FAILS TO START

1. Fuse out, causing an open circuit
2. Brushes not making proper contact
3. Line switch open
4. Bearings "seized" due to lack of oil
5. Motor overloaded. This will usually blow the fuse
6. Open field circuit at the terminal block or in the starting box
   "No voltage" release magnet burned out
7. Open armature or line connections, either at the motor or controller
8. Grounded winding, frequently blows the fuse
9. Brushes not set on neutral point
10. Armature wedged. Remove the wooden wedges from air gap of new machines
11. Dirty commutator or brush faces
12. High mica insulation on commutator preventing brush contact
13. Field coils short-circuited or grounded. Will usually cause excessive armature currents and blow the fuses
14. Reversed field connections. Test for polarity with a pocket compass
15. Low voltage
16. Pulley, gear, or coupling, may be tight against the bearing
17. Bent shaft, causing armature to stick on pole faces

18. Badly worn bearings allowing armature to rub field poles.
19. Burned out armature.

206. MOTOR STARTS TOO QUICKLY

1. Starting box resistance too low for the motor
2. Starting box resistance short-circuited
3. Insufficient time allowed for starting
4. Line voltage too high
5. Series motor without enough load for the starting resistance used with it
6. Too much resistance in field circuit.

207. MOTOR ROTATION REVERSED

1. Reversed field connections
2. Brush connections reversed or brushes in wrong position
3. Compound motor connected differential and starts in reverse direction from the series field. Speed will be high and torque very low
4. No field. Residual magnetism may start the motor in reverse direction on very light loads only. Motor will not start under heavy load
5. Wrong field connection in starting box. Armature resistance may be in series with the field.

208. SLOW STARTING OF MOTORS AND WEAK POWER

1. Low voltage
2. Resistance of starting box too high
3. Brushes off neutral, and will cause bad sparking
4. Motor overloaded
5. Heavy flywheel on driven machines
6. Weak field due to resistance in its circuit
7. Dirty or loose connections
8. Dirty or loose brushes
9. Brushes improperly spaced on commutator
10. Armature defects, shorts, grounds or opens
11. Wet armature or commutator.

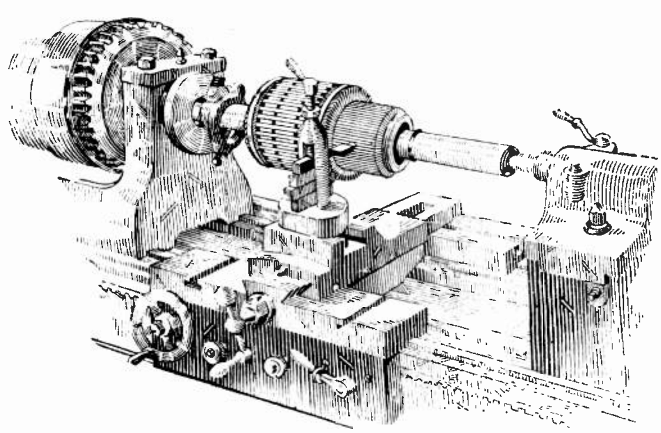

Fig. 154. Commutators that are badly burned or out of round can be resurfaced and trued up in a lathe as shown above.

209. MOTOR BUCKING OR JERKING

1. Overloaded motor
2. Reversed interpole polarity
3. Loose field connections which alternately open and close the field circuit and cause the motor to run jerkily
4. Wet or shorted field coils
5. Defects or loose connections in starting box.

210. MOTOR OVERSPEEDS

1. Open field circuit, may cause dangerously high speed
2. Shorted or grounded field coils
3. Load suddenly reduced on compound motor using field control
4. Brushes off neutral
5. Shorted or grounded armature conductors
6. Line voltage too high
7. Series motor overspeeds on light loads or no load.

211. SPARKING AT BRUSHES

1. Brushes or commutator dirty
2. Rough or burned commutator
3. High or low bars in commutator
4. Commutator out of round
5. Commutator segments shorted by carbon or copper dust in the mica slots, or by solder bridged across the bars
6. High mica
7. Brushes off neutral
8. Wrong type of brushes
9. Brushes poorly fitted
10. Brushes stuck in holders
11. Poor or unequal brush tension
12. Weak field, due to short circuits or grounds in the coils
13. Reversed field coils
14. Opens or shorts in armature winding. Opens usually cause long blue sparks and shorts are generally indicated by yellow or reddish sparks. The location of the defective coils will usually be indicated by burned bars to which they are connected
15. Oil grease or water on the commutator
16. Unequal air gaps due to worn bearings
17. Unbalanced armature winding
18. Bent shaft which causes brushes to chatter
19. Poor foundation, permitting vibration of the machine.

212. OVERHEATING OF MACHINES

1. Overloading will cause heat on both motors and generators due to excessive current passing through their windings and brushes
2. Excessive brush friction and brush tension too great
3. Brushes of too high resistance
4. Brushes off neutral
5. Damp windings
6. Excessive sparking at commutator, which may cause enough heat to melt the solder and loosen the armature connections
7. Opens or shorts in armature winding
8. Hot field coils caused by high voltage or short circuits in the coils

9. Field shunts loose or disconnected
10. Windings shorted by oil-soaked insulation
11. Hot field poles may be due to poor design causing eddy currents in the pole shoes. Unequal air gaps may cause field poles closest to the armature to heat
12. Hot bearings due to poor lubrication. May be caused by poor oil, stuck oil rings, or clogged oil wicks. Also caused by poor shaft alignment or excessive belt tension
13. Armature out of center with field poles, due to worn bearings. Causes excessive currents in parts of the armature winding and eddy currents in the field poles. Bearings should be repaired immediately
14. Clogged ventilating ducts
15. Loose connections between armature coils and commutator bars
16. Weak field, not allowing sufficient counter-E.M.F. to be generated to keep the armature current normal
17. Heat transfer through direct shaft connections from air compressors, steam engines or other machinery.

Normal operating temperatures of D. C. motors should not exceed 40° C. above the surrounding room temperature when operated at full load, or 55° C. at 25% overload for two-hour periods. If the machines are operated at temperatures above these values for any length of time, the insulation of the windings will become damaged and eventually destroyed. Safe operating temperature is about 140 to 150 degrees F.

213. UNUSUAL NOISES

1. Belt slapping due to a loose, waving belt
2. Belt squealing due to belt slipping on the pulley, caused by loose belt or overloads
3. Brush squealing due to excessive spring tension, hard brushes, or dry commutator surface. Application of a good commutator compound will usually stop the squealing due to a dry unlubricated commutator
4. Knocking or clanking may be caused by a loose pulley, excessive end play in the shaft, a loose key on the armature spider, or a loose bearing cap
5. Chattering vibration, caused by poor brush adjustment and loose brushes, hard brushes, or commutator out of round
6. Heavy vibration due to unbalanced armatures, bent shaft, or loose foundations.

214. GENERATOR TROUBLES. FAILURE TO BUILD UP VOLTAGE

1. Residual field lost or neutralized
2. Reversed field
3. Poor brush contact or dirty commutator
4. Open field circuit due to loose connections or broken wires
5. Field rheostat open or of too high resistance
6. Series field reversed so it opposes the shunt field
7. Shunts disconnected or improperly connected
8. Wet or shorted field coils
9. Too heavy load on a shunt generator
10. Residual magnetism reversed by flux from nearby generators.

215. POOR VOLTAGE REGULATION

1. Loose field shunts or connections
2. Poor regulation of engine speed
3. Belt slipping (if generator is belt driven)
4. Brushes off neutral
5. Improper resistance of field rheostat, or loose connections at this rheostat
6. Series field shunts not properly adjusted
7. Overheated field coils
8. Loose or grounded field wires between generator and switchboard
9. Armature out of center
10. Brushes improperly spaced
11. Weak field caused by short circuits or grounds in the field windings
12. Shorts, opens, or grounds in the armature coils
13. Excessive and frequent variations in load
14. Improper compounding

216. GENERATORS WILL NOT OPERATE IN PARALLEL

1. Poor speed regulation on prime mover, caused by improper governor adjustment
2. Open equalizer connections
3. Incorrect field shunts, open or loose field connections, or weak fields
4. Defective field rheostat
5. Wet field coils
6. Improper adjustment of series fields for compounding effects
7. Extreme difference in size, causing the smaller machine to be more responsive to load changes than the larger machine
8. Belt slipping, on belt-driven generators
9. Variations in steam pressure, on generators driven by steam engines
10. Defective voltmeter, causing operator to make wrong adjustment.

217. SYSTEMATIC TESTING

The preceding lists of common troubles and their symptoms are given to serve as a general guide or reminder of the possible causes of trouble in D. C. machines. They do not cover every possible trouble or defect, but intelligent application of the principles covered throughout these sections on D. C. equipment and careful systematic testing, should enable you to locate any of the troubles listed or any others.

Keep well in mind the advice previously given in this Reference Set, to the effect that even the **troubles most difficult to locate can always be found by methodically and systematically testing circuits and equipment.**

Let us remind you once more that any defect or trouble in electrical equipment or circuits **can be found**, and that **someone is going to find it.** It will be to your credit to be able to locate any and all troubles, and the best way to gain experience and confidence is to undertake willingly every trouble-shooting problem you can find. Go about it coolly and intelligently, use your knowledge of the principles of electricity and electrical equipment and circuits, and in this manner you will save a great deal of time and many mistakes.

You will also be surprised to find out how very simple some of the apparently baffling electrical troubles are, to the trained man who knows how to test and locate them.

218. TEST EQUIPMENT FOR LOCATING FAULTS

Some of the more common devices used for trouble shooting and testing are as follows:

1. Test lamp and leads
2. Magneto tester
3. Battery and buzzer tester
4. Voltmeter (portable type)
5. Ammeter (portable type)
6. Thermometer
7. Speed indicator
8. Wheatstone bridge
9. Megger:

Every maintenance electrician's kit should include a test lamp and a battery and buzzer test-outfit. These are very inexpensive and can easily be made up in a few minutes' time. It is a good idea to use two sockets and bulbs in series, for a test lamp which can be used either on 220 or 110-volt circuits. The two lamps will burn at full brilliancy when connected at 220 volts, and at one-half brilliancy on 110-volt circuits.

219. USE OF TEST LAMPS, BUZZERS AND MAGNETS

Test lamps of this type can be used for locating open circuits, short circuits, and grounds on the machines themselves or the wires leading to them. They are also very convenient for testing to locate blown fuses and to determine whether or not there is any voltage or the proper voltage supplied to the terminals of the machines.

The battery and buzzer test-outfit can be made of one or two dry cells taped together, with the buzzer taped securely to them. This unit should then be supplied with flexible test leads several feet long. The dry cells and buzzer can be located in a portable box if desired.

A simple test outfit of this kind can be used for locating grounds, opens, and short circuits on machines or circuits that are not alive.

The magneto test-outfit is very effective for locating high-resistance short circuits or grounds. These hand-driven magnetos generate voltage sufficiently high to break down the resistance at the point of the fault or defect, while a battery test set or test lamp used with ordinary line voltage might not show the fault.

When installing any new circuits to generators,

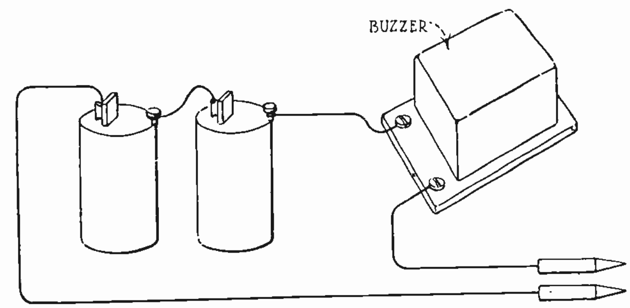

Fig. 155. A simple test set consisting of dry cells and buzzer is a very effective device for trouble shooting and locating of faults in electric circuits and machines.

motors, or controllers, the wiring should be thoroughly tested for grounds, shorts, and opens before connecting the machines.

An ordinary A.C. test magneto will ring through 20,000 to 40,000 ohms resistance. The use of magnetos above 50,000 ohms is not advised because they will ring through the insulation of conductors on long circuits.

In some cases an A. C. magneto will cause its bell to ring when the terminals are attached to the windings of very large machines, due to capacity or condenser effect between the windings and the frame of the machine. In such cases the ringing of the magneto doesn't necessarily indicate defective insulation.

220. USE OF PORTABLE VOLTMETERS AND AMMETERS

Voltmeters are very essential in plants having a great number of electrical machines and circuits. Voltmeters should be used for measuring line voltages or voltage drop on various circuits, to determine whether or not the proper voltage is supplied to the equipment.

It is very important that D. C. motors be operated at their proper rated voltage and not at voltages 10% or more below this, which sometimes results from overloaded line circuits and excessive voltage drop.

Low reading voltmeters are very satisfactory test devices for locating faults in armatures and field coils, as well as commutator defects. They can also be used for testing voltage drop in controller coils and resistors and to locate defective coils in this manner.

Ammeters can be used to measure the current through any circuit or machine and to determine whether wires or machine windings are properly loaded or overloaded.

One or more ammeters should always be available in plants where numerous electrical machines are to be operated and maintained.

221. THERMOMETERS

Thermometers should be used to determine the temperature at which various machines are operated, and especially if a machine is known to be operating somewhat overloaded. On machines that are not overloaded, if the temperatures rise above the rated temperature increase for a normal load, the cause should be determined and remedied at once.

By checking the temperatures at different points on a machine or its windings, the exact location of the fault or trouble can frequently be found by noting the points of higher temperature. Some thermometers for this use are marked with the centigrade scale, while others are marked with the Fahrenheit scale.

A convenient rule for converting the temperature in either scale to the other is as follows:

Temperature C. = 5/9 × (Temperature F. — 32)
Temperature F. = (9/5 × Temperature C.) + 32

222. SPEED INDICATORS

Speed indicators or revolution counters are commonly used to determine the speed of various machines. If machines are overloaded or thought to be operating at low voltage, it is often necessary to test their speed.

In other cases, checking the speed of machines may assist in locating certain faults within the machine or its own windings. In many industrial plants and factories it is very important that the motors driving production machines be kept operating at their proper rated speed, in order not to delay the production of the article being manufactured.

With the ordinary low-priced revolution counters or speed indicators, a watch with a second-hand can be used to check the time during which the revolutions are counted, and to get the speed in R.P.M.

Where a large number of machines are to be tested frequently, a higher-priced speed indicator known as a "tachometer" may be used. This device when placed against the shaft of any revolving machine indicates the speed in R.P.M. instantly.

223. IMPORTANCE OF RESISTANCE TESTS ON INSULATION

As previously mentioned, the megger and Wheatstone bridge are very effective devices for testing the insulation resistance of electrical machines and circuits. Regular inspection of the motors and generators with one or the other of these instruments will often save many serious cases of trouble or winding failures. In this manner it is also possible to prevent delays in production caused by the shutdown of machinery, on which the faults could have been located and repaired in advance by proper inspection and testing with such instruments.

In medium-sized and larger plants, instruments of this type will very soon save much more than their original cost.

Electric instruments are usually furnished by the employers or plant owners, although in some cases the maintenance man and electrician can well afford to own one or more low-priced portable instruments for the great convenience and aid they give in his work.

Whether these instruments are supplied by the employer or owned by the electrician, they should always be handled with proper care and intelligence.

Most meters are delicate devices and they should not be carelessly handled or banged around. Extreme caution should always be used not to connect ammeters across a line or in circuits with greater loads than the ammeter is designed for. The same warning applies to connecting voltmeters and wattmeters, which should never be connected to circuits of higher voltage than the instrument is made for.

224. COMMON TOOLS FOR MAINTENANCE WORK

A few of the more common tools used by the electrical maintenance man are as follows:

1. Knife
2. Pliers (side cutting)
3. Gas pliers
4. Screw drivers
5. Adjustable wrenches
6. Pipe wrenches
7. Machinist's hammer
8. Center punch
9. Cold chisels
10. Soldering iron
11. Blow torch
12. Tin snips
13. Bearing scrapers
14. Speed indicator
15. Air-gap gauge
16. Files; flat, round, and three-cornered
17. Hack saw
18. Breast drill

This list covers the more essential tools for ordinary jobs. Various other tools can be added for certain things, according to the class of work and equipment to be handled. A few good pointers in

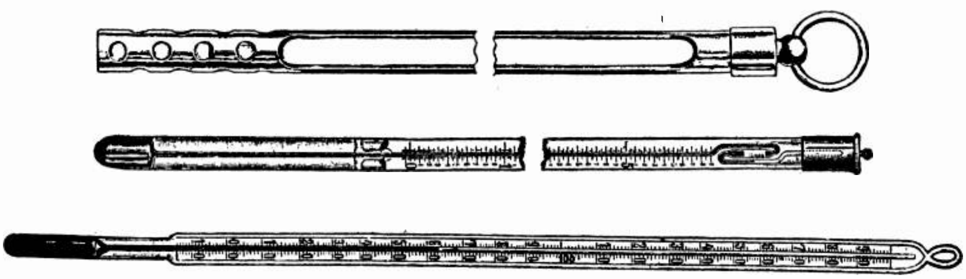

Fig. 156. Convenient thermometers of the above type are used for determining the temperature of the machine windings, by attaching the bulb to the windings with a small amount of putty.

the selection and use of these tools are given in the following paragraphs.

An electrician's knife should be a good substantial one, with one sharp blade that can be used for the removal of insulation from conductors, and one general utility blade for miscellaneous cutting, scraping, etc.

The most common and handy size of pliers is the 7-inch length, and if only one pair is used this should be the size. If one wishes to carry or to have on hand two or more sizes, the 6-inch and 8-inch sizes should also be included.

Cheap pliers never save any money, and only good pliers with strong jaws and good cutting blades should be purchased. Pliers larger than 9-inches are seldom used, except for the handling of very heavy wires and cables. Good pliers are made of the best grade of tempered steel and should never be held in the flame of a torch or allowed to become overheated in any way. Pliers should not be used to cut hard steel bolts or spikes.

The gas pliers are very convenient for holding cable lugs when heating them to melt solder and apply to cable ends, and for other general uses such as gripping bolts, nuts, and small parts. An 8 or 10-inch size is usually most convenient.

You should have at least three or four sizes of screw drivers and sometimes more. It is well to have one short and one long screw driver, both with points to fit a No. 7 wood screw; one short and one long driver to fit a No. 10 wood screw; and at least one large screw driver for No. 14 to No. 16 screws.

Never use a screw driver for a crow bar or chisel, as such abuse will only bend their bits or split the handles and render them unfit for the purpose for which they were intended.

If screw drivers become dull they can be carefully reground on the flat side of an emery wheel. Never grind them to a sharp point, as it tends to make them slip out of the slots in screws.

Adjustable wrenches should be of the 6-inch, 8-inch and 10-inch sizes, and these will handle all except the very heavy work. These tools are used for tightening bolts and nuts on motors, controllers, and all kinds of electrical equipment; and both for taking apart and re-assembling motors and machines to be repaired.

When using an adjustable wrench, always tighten the jaws securely on the nut before applying any pull on the handle, as this will avoid slipping and injury to the operator as well as "rounding" of the corners on nuts or bolt heads.

Never use a wrench upside down or backward, and don't hammer the handles, as it will only spring the jaws and spoil the wrench. Wrenches are made with handles long enough to apply by a steady pull all the pressure their jaws will stand.

Pipe wrenches should be used for loosening stubborn or worn nuts on which the adjustable wrench slips, and also for making BX or conduit connections. One 10-inch and one 12-inch pipe wrench will usually be sufficient for ordinary repair work.

A good hack saw is indispensible for cutting bolts, BX, conduit, and heavy cables. Usually the 12-inch rigid or non-adjustable frame is best, and several good sharp blades should always be on hand for this saw.

When using a hack saw, the object to be cut should be securely held in a vise or clamp. If the object is allowed to wobble or twist it will crack the teeth out of the saw blade.

A machinist's hammer of one lb., one and a half lbs., or two lbs. weight will usually be found most convenient.

Center punches are very handy for marking places for drilling holes in metal, or for marking the end-plates of motors or machines before they are removed, so you can be sure of getting them replaced properly.

A small breast drill or Yankee drill with a dozen or more short drills will be found very convenient in making many time-saving repairs.

Several sizes of cold chisels are needed for cutting bolts, screws, metal strips, etc., on which the hack saw cannot be conveniently used.

Tin snips are very convenient for cutting strips of hard insulation, such as fibre, or for cutting shims of thin metal for lining up bearings or machine bases. They can also be used for cutting shims to place under field poles when adjusting air gaps on the poles of motors or generators.

A set of bearing scrapers, such as used on automotive work are usually very convenient. These are to be used for scraping sleeve-bearings to fit the shafts of motors or generators.

An air-gap gauge consists of a group of thin metal feeler gauges that can be used for determining the air gap between the armature core and various field-pole faces.

It is quite important to keep the armature centered in the machine, in order to secure best operation, and when bearings become worn and allow the armature to drop below the center, an air-gap gauge can be used to re-center the armature or determine which poles it is closest to.

One or more pieces of hack saw blade can be easily fitted with file handles and used for undercutting mica on small and medium-sized machines, as was explained in a previous article.

Flat files are very convenient for resurfacing and dressing the faces of contacts on controllers, and hundreds of other uses which are not necessary to mention, as most everyone knows the common uses for a file.

Where most of the work to be done is within reach of electrical circuits of the proper voltage, an electric soldering-iron is generally most convenient. Where electric supply of the proper voltage is not available or where very heavy soldering is to be done, a blow torch is essential. One or more soldering coppers can then be used, by heating them in the flame of the blow torch.

225. OPERATION AND CARE OF BLOW TORCHES

At this point it will be well to give a few general hints on the use of gasoline blow-torches.

A torch of one quart size is usually most convenient for ordinary work. To fill the torch, unscrew the cap in the bottom and pour the gasoline in the opening with a funnel. If any gasoline is spilled on the bottom of the torch it can be run inside by gently rocking the torch back and forth until most of it runs into the opening.

After filling, replace the cap, making sure that the composition washer is in place, to seal the torch air-tight and prevent leakage of gasoline. Tighten the screw cap securely and pump a small amount of air into the tank. Six to ten strokes of the pump is sufficient for starting a torch. Then hold the hand or some object over the torch nozzle, tipping the torch back slightly, and open the needle valve a small amount. The gasoline which is allowed to escape will then drain into the small vessel or cup under the torch. The cup should be nearly full before the valve is closed.

This gasoline should then be carefully ignited with a match and allowed to burn away almost completely before opening the valve again.

This flame heats the torch nozzle and gas generator so the liquid gasoline will be turned into vapor as it escapes. This is necessary for proper operation and to secure the full heat of the flame.

When the torch is well-heated, open the needle valve and adjust it until the flame is a sort of blue color with a slightly pink tinge.

If the torch is operated in a breeze or wind, turn the torch so the flame points against the breeze. This will tend to confine the heat of the flame where it will do the most good and keep the torch hot enough to operate.

When through using the blow torch, it should be extinguished by closing the needle valve; never by blowing or smothering the flame. After extinguishing the torch, let it stand a few minutes; then open the needle valve until a hissing sound is heard. This relieves the pressure in the tank and the needle valve can then be close gently and the torch put away until it is to be used again.

Never use a pliers on the needle valve or you may damage the soft metal seat of the valve. **Never use one blow torch to heat another, or it may result in an explosion and dangerous burns.**

These few general hints on the types of tools and the methods of their use are intended simply to aid those who have never used tools of this kind to become properly acquainted with them.

Thoughtfulness, pride, and care in your work, and the application of a little mechanical ability along with practice, are all that are required to make most anyone proficient in the use of these tools and in ordinary electric maintenance work.

Always do all repair work neatly and thoroughly. You will find that in the long run it saves time and trouble. Take a reasonable pride in all electrical machinery and equipment which you may be operating or maintaining, and also in your knowledge of the proper operation and care of this equipment.

Conscientious and intelligent application of the knowledge you can gain from this section, along with the actual experience obtainable on D. C. machines in this department of the shop course, should enable you to qualify in the operation or maintenance of practically any Direct Current equipment.

NOTES

NOTES

NOTES

COYNE
Electrical School
CHICAGO ~ ~ ILLINOIS

ESTABLISHED 1899

ALTERNATING CURRENT
AND
A. C. POWER MACHINERY

Section One

Nature of Alternating Current
Generation of Voltage, Sine Curve, Values, Frequency
Single-phase and Polyphase Currents
A. C. Circuits
Inductance, Capacity, Impedance
Ohms Law for A. C., Circuit Calculations
Power Factor
Lagging and Leading Currents
A. C. Power Problems
Power Measurement
Meter Connections

ALTERNATING CURRENT

Alternating current electricity provides one of the greatest fields of opportunity and one of the most fascinating branches of work and study in the entire electrical industry today.

In the last few years, alternating current and A.C. machines have come into such extensive use in nearly all industries that no electrical man can afford to be without a knowledge of this very interesting form of energy and equipment.

One of the greatest advantages of alternating current is that it can be much more economically transmitted over long distances than direct current can. This is due to the fact that the voltage of alternating current energy can easily be stepped up to very high values by means of transformers.

The economical high-voltage transmission of alternating current makes it possible to generate this form of energy more cheaply in large and efficient central generating stations or power plants, and then transmit it to towns and factories at considerable distances.

High tension transmission lines also make possible the use of water power produced in large hydro-electric plants which are often a long distance from the towns and places where the electrical energy is used.

Thousands of miles of high-voltage transmission lines, operating at voltages from 66,000 to 220,000, tie together the great steam and hydro generating stations in vast super-power networks throughout this country. These lines carry hundreds of thousands of horse-power of clean, silent, and efficient electric energy to turn the wheels in our great factories, to light our homes and city streets, and to operate electric railroads, etc.

Interconnection of the greatest power generating plants and centers by high voltage A. C. lines makes possible greater economies of operation and dependability of electric supply than can be obtained in any other way. It tends to balance or equalize the varying loads of the different towns, communities, and factories, into a more uniform average load on all of the interconnected generating plants: and thereby reduces the number of spare generators that must be carried in any of the plants for peak loads. Connecting a great number of power plants together also makes it possible for one generator, plant, or line to be shut down for repairs without interrupting the electric supply to the users, as the full load can be carried temporarily by the other plants on the system.

For these reasons, alternating current transmission lines have been developed with tremendous rapidity so that at present their voltages run as high as 290,000, and new power lines are constantly being installed in a great network throughout the entire country. Engineering tests and experiments are now being carried on toward the development of 330,000-volt transmission lines.

Even with our present super-power lines it is possible to economically transmit many thousands of horse power over distances of several hundred miles.

Great generating plants in Chicago have supplied power to the city of Pittsburg, and have for a short test period supplied power to light the streets of Boston. Chicago has some of the largest generating plants in the world, and these plants are connected with others in a vast system with transmission lines reaching to the eastern and southern coasts of the U. S., and long distances north and west.

Great steam generating plants producing from 100,000 kw. to 500,000 kw. each feed the alternating current to the transmission lines; and new power plants are constantly being built to supply the ever-increasing demand for electric power.

It is almost impossible to comprehend the tremendous rate at which alternating-current electrical equipment has been developed, and the present rate of expansion of this great industry.

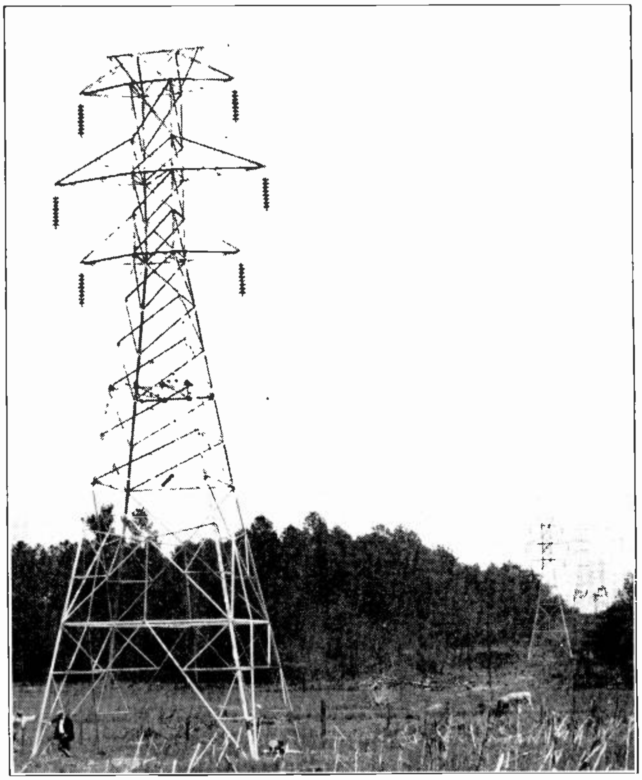

Fig. 1. This photo shows a high voltage power line of the type which carry thousands of h. p. of electrical energy throughout the country.

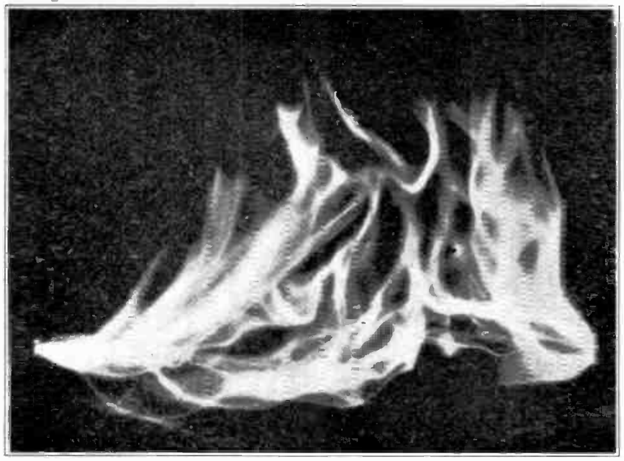

Fig. 2. The above view shows a high voltage arc created by passing current at a potential of several hundred thousand volts through air.

In 1889 an A. C. generating unit of 400 kw. capacity was put into operation, and was thought to be a very large unit at that time. The size of A. C. generators kept increasing until, in 1917, units of 45,000 kw. were in use, and a unit recently installed in one of Chicago's new power plants is of 208,000 kw. capacity. This is equivalent to about 275,000 h. p. Fig. 3 shows a mammoth steam-turbine-driven A. C. generator of 165,000 kw. capacity.

Hydro-electric plants have also developed rapidly. In 1890 only a few thousand h. p. were produced at Niagara Falls, but now its electrical output has been increased to over one million h. p.

A new hydro plant of the Philadelphia Electric Company, at Conowingo, Maryland, produces nearly one-half million h. p. of electric energy; and there are hundreds of other water-power plants which generate from 10,000 to 100,000 h. p. and more each. Fig. 4 shows a photo of the great dam and power house at Conowingo.

The operating of all these steam and hydro-electric power plants provides steady jobs at good pay and clean, fascinating work, for many thousands of trained electrical men. The construction of new plants and power lines, and the inspection and maintenance of existing lines, employs thousands more.

Then there is the manufacture, installation, and maintenance of the vast number of A. C. electrical machines and devices that use the millions of h. p. generated by all these power plants.

Electrical manufacturers produce approximately

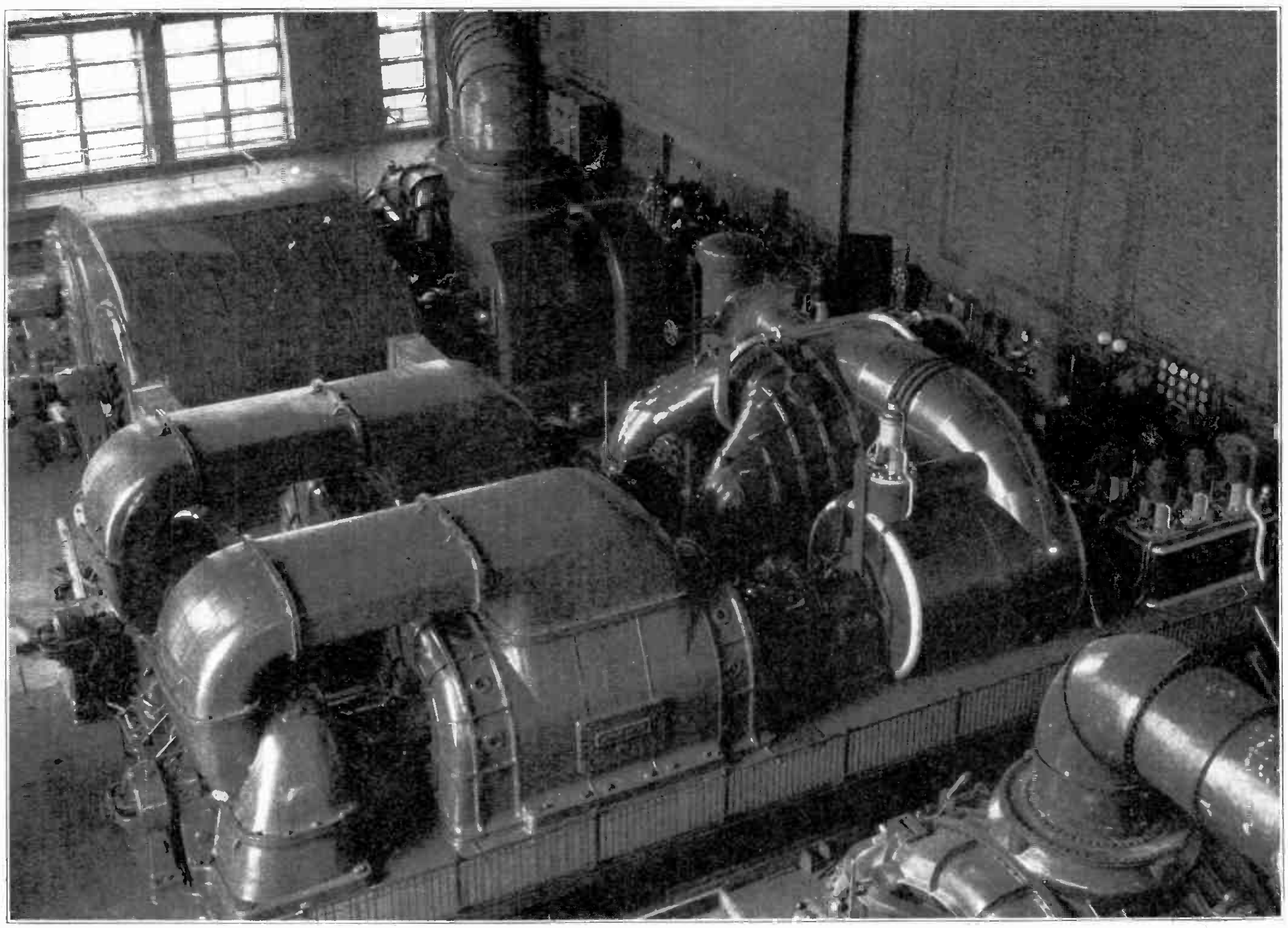

Fig. 3. Modern steam generators of the above type produce many millions of h. p. of electrical energy, for use in lighting and the operation of power machinery. The generator shown in this photo is of 165,000 kw. capacity and is driven by steam turbines. (Photo courtesy of American Brown Bovery Co.)

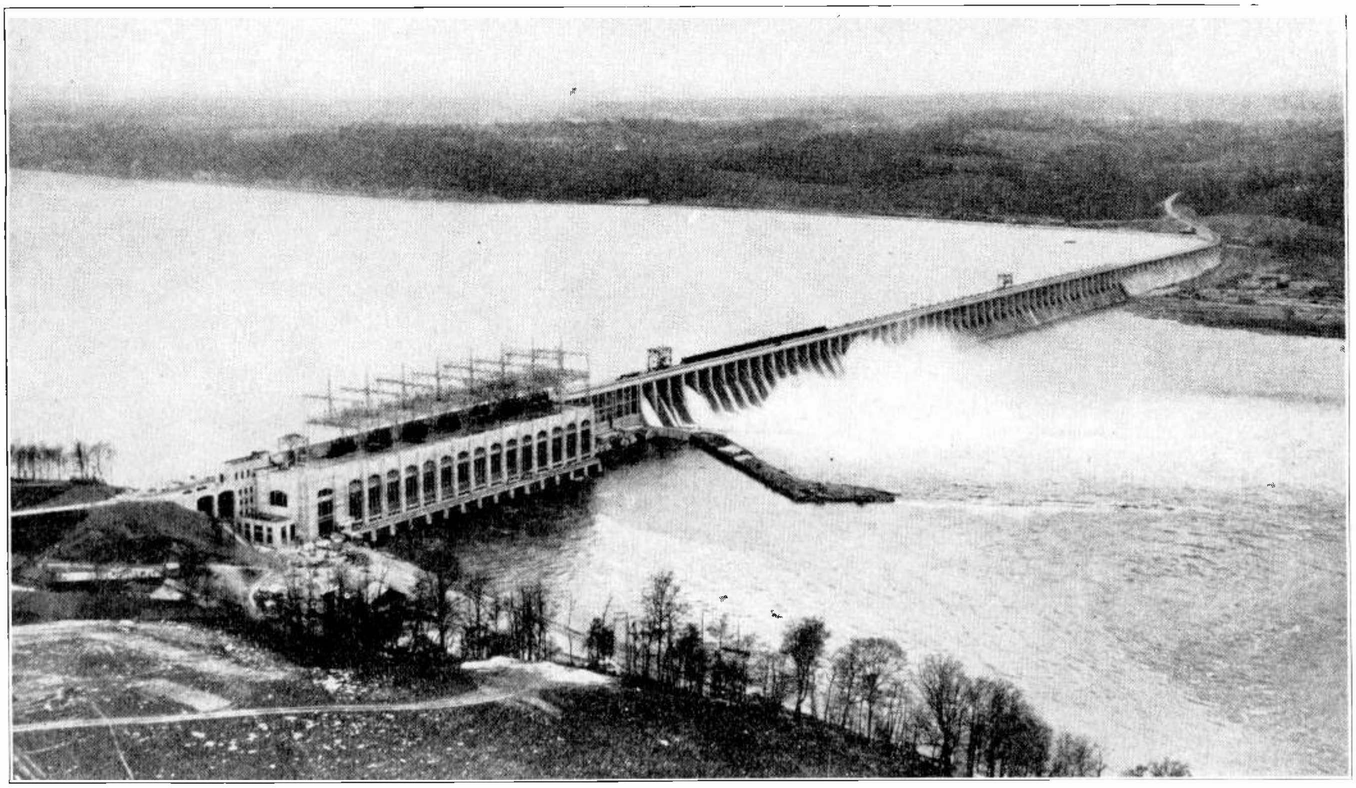

Fig. 4. Enormous hydro-electric generating stations also produce many millions of h. p. to supply the extensive needs for electrical energy. This hydro plant is at Conowingo, Md., and is one of the largest in this country. It produces several hundred thousand h. p. (Photo courtesy Philadelphia Electric Co.)

2½ billion dollars worth of electrical equipment yearly. Try to imagine, if you can, the additional number of men required each year to produce, install, operate, and maintain that equipment.

Approximately 80% of all the money invested in the electrical industry in the U. S. is invested in sixty-cycle, A. C. equipment; and about 90% of all the electric power generated is A. C. So you can readily see the value of a good knowledge of this branch of electricity.

Manufacturing and industrial plants in this country are over 80% electrified at present. The machines in these plants are largely driven by A. C. motors, because of their practically constant speed, rugged construction, and low maintenance costs. Fig. 5 shows a typical example of A. C. motors used for individual drive of machines in a textile mill.

The most common type of A. C. motors have no commutators or brushes, which greatly reduces their wearing parts and the amount of care they require.

Special types of A. C. motors with high starting torque have been developed for certain uses for which D. C. motors were formerly considered necessary, and now there are A. C. motors available for practically every need.

Alternating-current synchronous motors are ideal for operating equipment where absolutely constant speed is required.

In addition to the hundreds of thousands of h. p. used in A. C. motors, factories also use alternating current very extensively for spot welding and butt welding machines, enameling ovens, heat-treating furnaces, and other processes, as well as for lighting.

Sixty-cycle alternating current is very suitable for lighting with incandescent lamps, as the periods of zero voltage between the alternations are so very short that they do not allow time for any noticeable dimming of the light from the lamp filaments. So wherever alternating current is used for power purposes it is also used for lighting; and in homes, offices, and stores alternating current is by far the most generally used for lighting.

Some very important branches of the electrical industry actually depend upon alternating current for their existence. Radio is one of these, and as the energy used in radio transmission is high-frequency A.C., the study of alternating current principles is very essential to anyone who plans to follow radio work.

The increase in the use of alternating current in the last few years and the thousands of uses which have been developed for it so far, make it almost impossible to over-estimate the extent to which A. C. will undoubtedly be used in the near future.

The high rate of development and expansion in this field requires thousands of additional trained men yearly. There are many of electricians in the field today who have followed D. C. work almost exclusively and know very little about the principles of alternating current and A. C. machines.

Therefore, this branch offers the finest of opportunities to trained practical men who have a good knowledge of alternating current.

And let us emphasize again that, in addition to being a very valuable subject to know, alternating current electricity is one of the most fascinating and interesting subjects any ambitious student can ever hope to find.

Alternating current differs from direct current in many ways, but practically all the principles of electricity which you have learned so far can, with a few modifications, be easily applied to A.C.

Alternating current is often thought to be a difficult subject to master. It does not need to be at all, when properly explained in a practical manner.

In the following pages the principles of alternating current and the operation and care of A. C. machines will be covered in a simple non-technical manner, for the needs of the practical man.

Study these pages carefully for the sake of your future earning capacity, and to qualify yourself for some of the splendid opportunities in this field.

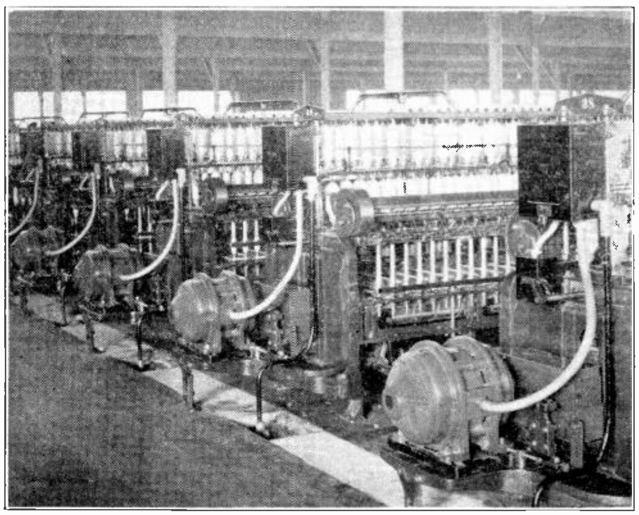

Fig. 5. This view shows a number of A. C. motors being used for individual drive on machines in a textile mill. Thousands of factories and industrial plants use electric motors in this manner for driving their various machines and equipment. (Photo courtesy G. E. Company)

1. NATURE OF ALTERNATING CURRENT

In previous sections of this Reference Set we have already explained to some extent the difference between alternating current and direct current. We shall, however, review some of these points and also take up others in detail, as it is very important to have a thorough understanding of the nature and principles of alternating current, in order to properly understand the operation of A. C. machines.

Alternating current is current that constantly changes in value and periodically reverses in direction.

This reversal of the current is caused by the armature conductors passing first a north and then a south pole in the generator.

You have learned that A. C. is induced in the conductors of any ordinary generator armature, and that to obtain D. C. we must rectify the current from a generator armature by means of a commutator.

Alternating current can be made to produce heat, light, and magnetic effects just as D. C. can. The principal difference in the magnetic fields of A. C. and D. C. circuits is that alternating current produces a constantly varying flux, **the lines of which are always in motion or expanding and contracting around the conductor.** This alternating or moving magnetic field of alternating current is what makes possible the operation of transformers, to step the voltage up or down as desired.

2. INDUCTANCE AND CAPACITY IN A. C. CIRCUITS

The moving A. C. flux also sets up in any A. C. circuit, **self-induction** due to **inductance.** This inductance and also a condenser effect, or **capacity,** which is caused by the constantly varying voltage of A. C. circuits, are the two principal differences between A. C. and D. C. circuits.

We have learned that the important factors in any direct-current circuit are **pressure, current,** and **resistance.** We have the same three factors to consider in any A. C. circuit and also the two additional factors—**inductance** and **capacity.**

Ohms law applies also to A. C. circuits, with a slight modification to include the inductive and capacity effects on the current, as well as the effects of resistance.

Many of the most important advantages of A. C. and many of the greatest achievements in the electrical industry are based on these two additional factors in A. C. circuits—namely, **inductance** and **capacity.** They will both be thoroughly explained a little later.

3. GENERATION OF ALTERNATING VOLTAGE

The development or generation of alternating-current voltage is shown in Fig. 7. At the left

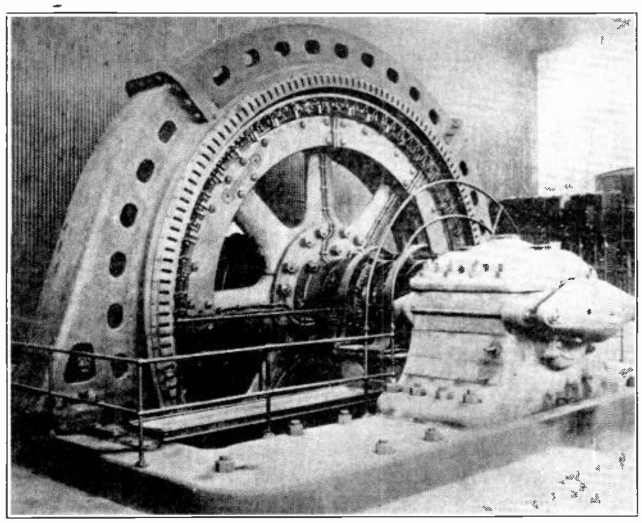

Fig. 6. This large A. C. induction motor is in use in a steel mill and is rated at 6500 h. p. (Photo courtesy G. E. Company)

of this figure is a sketch of a simple two-pole generator in which the progress of the conductor throughout one revolution is shown in eight steps of 45° each. The successive values of voltage which will be induced in this conductor are plotted or projected along a horizontal base-line at the right side of the figure.

The values above the line are positive voltage values and those below the line are negative. Electrical degrees and time are also plotted along this axis line. The electrical degrees are represented by spaces of uniform length and drawn to scale, for example ¼-inch for each 45 degrees, or ½-inch for each 90 degrees, etc.

Other spacing values can be used to suit the size of the drawing desired.

Time "later" is indicated in a right-hand direction and time "earlier" in a left-hand direction. To illustrate this, a vertical line "X Y" is drawn through the axis; and all values on the right-hand side of this vertical line are later in time, while all values on the left are considered to be earlier in time.

While the conductor shown at No. 1 is moving in the neutral plane of the magnetic field it will have no voltage induced in it. Therefore, the voltage value at this point will be as shown at "a" on the axis line. The axis line always represents zero voltage value.

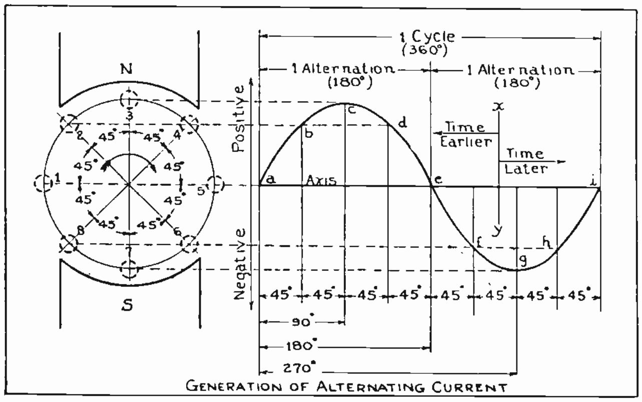

Fig. 7. The above diagram illustrates the manner in which alternating voltage is produced in a simple two-pole generator. The sine curve shows the variations and reversal of voltage for one revolution of the armature. Study this diagram very carefully with the accompanying explanation.

As the conductor moves around the armature 45 degrees in a clockwise direction it comes to position 2, where it is beginning to cut into the field flux of the N pole, and at a more and more abrupt angle. At this point the voltage value will be as shown at "b", or the point where the dotted line running to the right from conductor 2 intersects the vertical time line which is just 45 degrees later than the one at "a".

When the conductor moves another step, or 45 degrees, farther to position 3, it will then be cutting at right angles to the dense flux of the N pole, and will produce a voltage value as shown at "c", where the dotted line from the conductor intersects the time line, which is now 90 degrees later than the one at "a".

When the conductor moves to position 4 it is beginning to leave the flux from the N pole and its induced voltage will be somewhat lower, as shown at "d". As the conductor moves on to position 5 it is again passing through the neutral plane or at a point where it doesn't cut any appreciable amount of flux, and its voltage will again be at zero value, as shown at "e".

The voltage values which this conductor will produce in passing from position 5 back to 1 will be the same as those from 1 to 5, except that the voltage will be in the reverse direction, as the conductor is now cutting in the opposite direction through the flux of the S pole. These negative values are represented at the points, f, g, h, and i, or below the axis line.

The armature conductor has now passed through a complete set of positive and negative values and through one complete revolution or 360 electrical degrees.

4. SINE CURVES; ALTERNATION, CYCLE, FREQUENCY

If we connect the points a, b, c, d, e, f, g, h, and i all together with a curved line, that line will form what is known as a **sine curve.** This curve gives us a clear mental picture of the manner in which the voltage varies in amount or value and reverses in direction in an alternating-current circuit.

The values from "a" to "e" are all positive and constitute 180 E°, or one **alternation.** The values from "e" to "i" form the negative alternation. These two successive alternations, one positive and one negative, complete one **cycle.**

If we were to go on revolving the conductor rapidly it would produce one cycle after another of alternating current, provided the coil were connected to a closed circuit. The number of these cycles which occur in each second of time is called the **frequency** of an alternating current circuit, and is expressed in cycles per second. Nearly all A. C. systems in this country today use 60-cycle frequency.

Examine the diagram in Fig. 7 very carefully, until you are sure you know the number of electrical degrees in one alternation and in one cycle.

A conductor in a generator must always pass one pair of poles, or one north and one south pole, to complete a cycle. Therefore, the greater the number of poles in a generator the greater will be the number of cycles it will produce per revolution. The frequency of any A. C. generator can always be determined by the following simple formula:

$$f = \frac{RPM}{60} \times N$$

In which:

f = frequency in cycles per second
RPM = revolutions per minute of generator
60 = no. of seconds per min.
N = no. of pairs of poles in generator

5. FLOW OF ALTERNATING CURRENT

If an alternating voltage such as shown in Fig. 7 is applied to a closed circuit, alternating current will flow. The current will, of course, vary in amount and reverse in direction, just as the voltage does. These alternations or impulses of current can be shown by a curve similar to the one for voltage in Fig. 7. Current first starts to flow around the circuit in one direction, and continues in this direction during one alternation, or 180°. In a 60-cycle circuit this would be for $\frac{1}{120}$ part of a second.

During this period the current value or intensity keeps gradually increasing up to maximum during the first 90°, or one-half alternation. Then it starts to decrease in amount, but continues in the same direction for another 90°, or the last half of the alternation.

When the current in this direction has fallen to zero value, it then reverses and flows in the other direction for one alternation or $\frac{1}{120}$ part of a second, again rising and falling in value or amount.

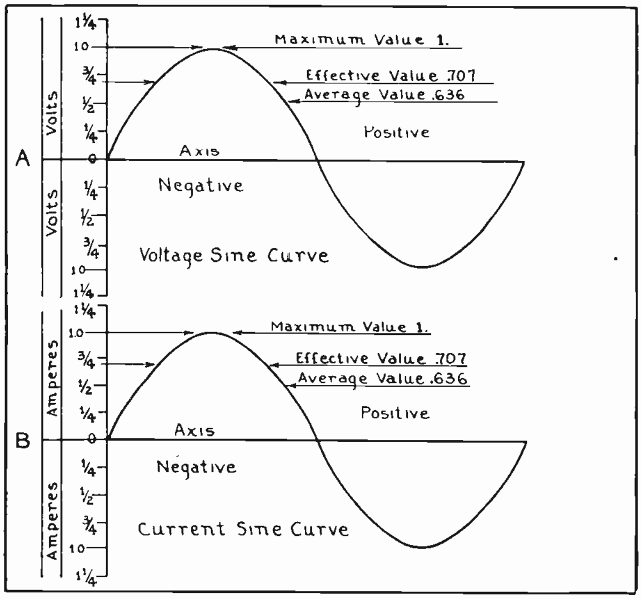

Fig. 8. These sketches show the maximum, effective, and average values of alternating voltage and current.

6. MAXIMUM AND EFFECTIVE VALUES OF ALTERNATING CURRENT

Fig. 8-A shows a curve for one complete cycle of single-phase alternating voltage, and Fig. 8-B shows a curve for the current that we will assume is caused to flow by that same voltage cycle.

These curves show **maximum values** of one volt and one ampere for this circuit. You will note that these maximum values last for only a very short period during each alternation. So, if we were going to determine the heating effect or power that would be continuously produced by such an A. C. circuit with one volt maximum pressure and one ampere maximum current, we could not expect as great a result as from a D. C. circuit with one volt continuous pressure and one ampere continuous current.

By actual test we find the heat produced by the A. C. circuit is about 70%, or to be more exact .707 of that produced by the D. C. circuit.

We therefore say that the **effective** voltage and current values of an A. C. circuit are .707 of the maximum values. It is this effective value that we consider in ordinary work and calculations with A. C. circuits. **Ordinary A. C. voltmeters and ammeters are calibrated to read the effective values and not the maximum values.**

Therefore, if an A. C. circuit has meter readings of 100 volts and 100 amperes, we know these to be the effective values; and this circuit would produce just as much heating effect as a D. C. circuit of 100 volts and 100 amperes.

Compare carefully the effective and maximum values shown in Fig. 8. You will note that the effective value is nearly three-quarters of maximum value.

If an A. C. circuit has a maximum voltage value of 100 volts, the effective value would be $.707 \times 100$, or 70.7 volts.

7. CALCULATION OF EFFECTIVE AND MAXIMUM VALUES

The effective values of an A. C. voltage or current curve for any alternation, can be calculated by what is called the **root mean square** (R.M.S.) method.

This calculation is made by getting the instantaneous values of the curve at points one degree apart and squaring all these values. Next all these squares are added together and averaged, by dividing the sum by the number of squares. Then, taking the square root of this average, we would have the root mean square; or, in other words, the square root of the average square of the separate values.

This method of squaring the curve values and then getting the square root to obtain the effective value, is used because the **heating effect of any A. C. circuit is proportional to the square of current at any instant.**

The process just described may seem somewhat technical, but with a little reviewing you will find that the principle is quite simple.

You may not have occasion or need to use the R.M.S. method in any calculation in your ordinary electrical work for some time; but it may be very handy for some future reference, so it is given here for your convenience at any later time. It is also given as a matter of interest, so you may know how the effective value is obtained and where the figure .707 comes from.

Remember that an A. C. circuit will perform just as much work per volt and per ampere as a D. C. circuit, because ordinary A. C. meters read the effective values only, and these are the values commonly considered in A. C. work.

One of the most important points to be considered, however, is that to produce a given effective voltage in an A. C. circuit, the maximum voltage for its short periods during each alternation will be considerably higher than the effective voltage registered by the meter. This places a higher voltage strain on the insulation of an A. C. circuit of a given effective voltage value, than on a D. C. circuit of the same voltage.

When either the maximum or effective value of an A. C. circuit is known, the other can be found by one of the following formulas:

Effective value = Max. value × .707
Maximum value = Eff. value ÷ .707

It is often easier to multiply by the reciprocal of a number than to divide by the number itself, and the same result can be obtained by either method. You will recall that the reciprocal of a number is equal to 1 divided by the number. So, in the case of the effective value .707, its reciprocal is equal to $\frac{1}{.707}$, or 1.414.

Accordingly, the above formula for finding maximum value can be changed to read:

Max. value = eff. value × 1.414

The use of this formula is illustrated by the following example.

If we have a motor which is being rewound to operate on a 2200-volt circuit, what would be the maximum voltage stress on its insulation?

If the effective value is 2200 volts, then:

Max. value = 2200 × 1.414, or 3110.8 volts

This would be the maximum voltage impressed on the insulation of the motor winding and, allowing enough extra for safety factor to prevent possibility of puncture of the insulation, it would probably be insulated for 5000 volts or over.

8. AVERAGE VALUE OF ALTERNATING CURRENT

By referring again to Fig. 8, you will note that an **average value** of the curves is also shown. The average value is .636 of the maximum value. This figure is used in a few electrical calculations and in the design of electrical machines, but not a great deal in ordinary electrical work.

Because of the shape of the sine curves for alternating current and the fact that the heating effect is proportional to the square of the current values, the effective value is actually a little higher than the average value, as shown in Fig. 8.

The voltage alternations produced by an actual power generator would not be quite as smooth or perfect in shape as the curves shown in these figures. Instead they would have little irregularities or ripples in them; but as they follow the same general shape, all ordinary circuit calculations for A. C. are based on the true sine curves as shown.

9. SINGLE-PHASE AND POLYPHASE CURRENTS

You have already learned that A. C. circuits are of **single-phase, two-phase**, and **three-phase** types; and in the section on A. C. armature winding the method of generating single-phase and polyphase currents was explained. If you find it necessary to refresh your memory on these points, review pages 1 to 5 of Section Two of Armature winding.

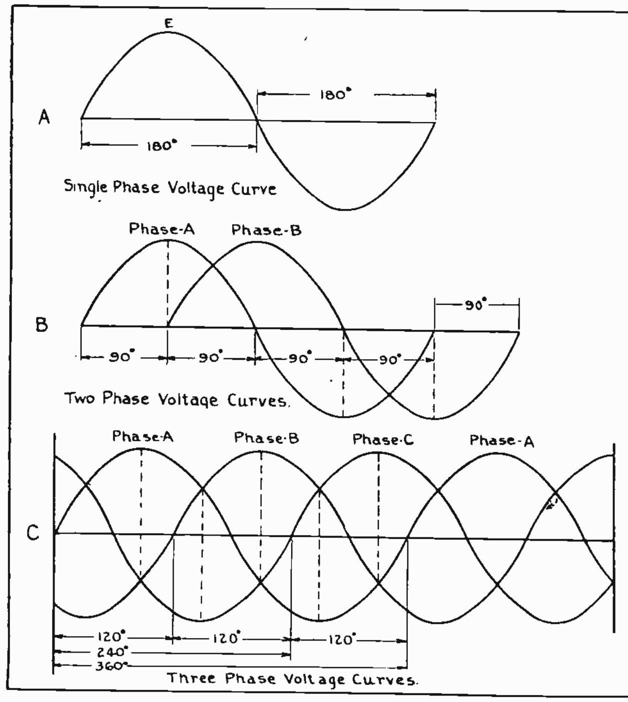

Fig. 9. The above diagram shows the sine curves for single-phase, two-phase, and three-phase alternating voltages.

You will recall that the term "phase" refers to the number of parts of an A. C. circuit or the number of separate sets of alternations in the circuit.

Fig. 9 shows three sets of curves for single-phase, two-phase, and three-phase circuits. The single-phase curve at "A" has successive alternations of 180° each. The two-phase circuits have two sets of alternations occurring 90° apart; that is, they start, reach their maximum values, and finish always 90° apart. Three-phase circuits have three sets of alternations, 120° apart, as shown at "C" in the figure.

You will recall that these alternations are generated with the various spacings in degrees, by spacing the armature conductors the same number of electrical degrees in the generators.

Each alternation of any single-phase or polyphase circuit consists of 180°, and each cycle consists of 360°. Keep in mind also that the poles in an alternator are always spaced 180 electrical degrees apart, and that a pair of poles constitutes 360 electrical degress.

Six-phase energy is also used in some cases, for converters and rectifiers. Fig. 10 shows a set of curves for six-phase energy. Two-phase circuits are still used to some extent in older installations. Single-phase and three-phase systems are by far the most commonly used. Single-phase systems are used extensively for incandescent lighting and small power motors, and three-phase systems are used almost exclusively for large motors, general power work, and transmission lines.

10. PHASE RELATIONS OF VOLTAGE AND CURRENT

The voltage and current of an A. C. circuit can both be shown in the same diagram by separate sets of curves drawn along the same zero or axis line, as shown in Fig. 11. This figure shows the curves for a three-phase circuit. The solid lines represent the voltage impulses and the dotted lines represent the current impulses.

In this diagram the current value is shown to be slightly less than the voltage value by the lower height of the curves; but the current alternations are **in phase** or in step with the voltage alternations. In other words, the current and voltage alternations of each phase start together, reach their maximum values together, and finish together.

This seems to be the proper or natural condition, as you know that the current variations are caused by the variations in pressure or voltage; so it would seem quite natural that the two should be in step, or "in phase", as we say.

It is possible, however, to have the current impulses occur **out of phase** with the voltage impulses in A. C. circuits, due to the effects of inductance or capacity in these circuits.

The current may either **lag** or **lead** the voltage, according to whether the inductance or capacity is greatest in the circuit. These conditions will be fully explained a little later.

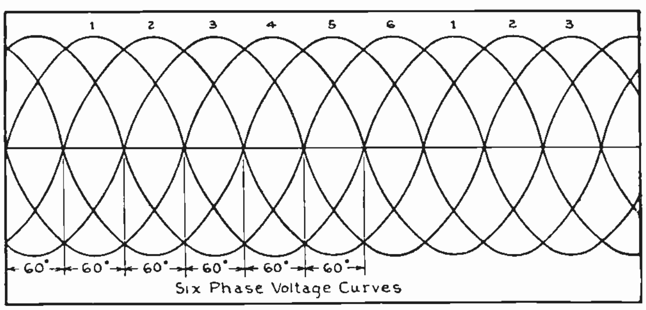

Fig. 10. This sketch shows the sine curves for the voltage of a six-phase A. C. circuit. Compare these sketches carefully with the ones in Fig. 9, and note the number of degrees spacing between each phase and the next.

11. EFFECT OF LAGGING OR LEADING CURRENT ON POWER

When the current and voltage impulses are in phase with each other, or working together in the same direction, they will, of course, produce more useful power in watts than when they are out of phase or working in opposite directions part of the time.

When current and voltage are in phase as shown in Fig. 12, the product of the voltage and current values at any instant will give the watts power at that instant.

The power curve in this diagram is shown by the heavy line, and is all above the axis line, representing useful power.

In Fig. 13 the voltage and current are slightly out of phase, and the current is lagging a few degrees behind the voltage. This causes short periods during each alternation when the voltage and current are in opposite directions, as shown between the lines "a" and "b". During this period there is no useful power in watts produced and the power curve is shown below the axis line, representing what is known as **wattless power.**

This wattless power does not produce any useful power on the system, but merely produces additional heating of the conductors, and thereby limits the capacity of generators, motors, and lines in which this condition exists.

When multiplying the values of voltage and current curves to obtain the power in watts at any instant, the polarity of the curves must be carefully observed. When voltage and current curves are of the same direction or polarity, their product will all be positive or useful watts, and is shown by the power curve above the axis line. At points where the voltage and current curves are of opposite polarity, their product will give negative or wattless power, shown by the power curve below the axis line.

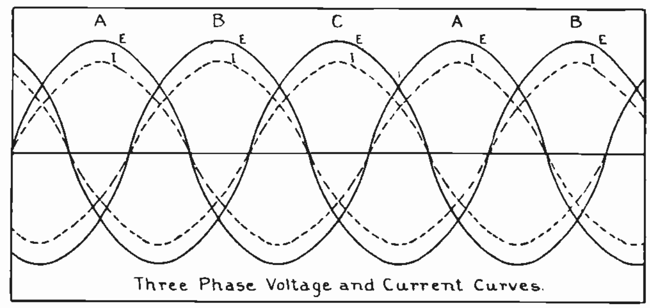

Fig. 11. Voltage and current curves of a three-phase circuit. The voltage is shown by the solid lines and the current by the dotted lines.

12. A. C. CIRCUITS

The practical man will often have occasion to make simple measurements and calculations with the voltage, current, and power of A. C. circuits, in his work in the field as an electrical construction man, power plant operator, or maintenance man.

These calculations can be made with A. C. circuits in very much the same manner that you have already learned for D. C. circuits; and just as easily, once you have a thorough knowledge of A. C. principles and the important factors which control the current and power in A. C. circuits.

It is sometimes difficult for a student to see how these calculations can be made with A. C., because of the manner in which the voltage and current are continuously and rapidly varying in value and re-

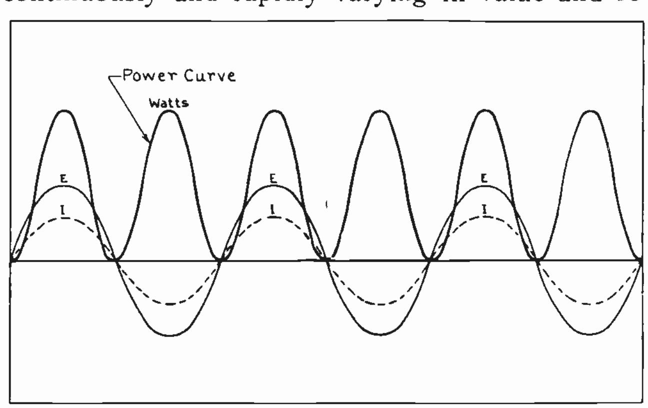

Fig. 12. This diagram shows the curves for the voltage, current, and power of single-phase A. C. circuit, in which the voltage and current are in phase with each other.

versing in direction. It is our purpose to simplify these points and avoid the unnecessary misunderstanding and difficulties which so frequently worry students and electricians who do not have a proper understanding of the simple fundamentals of alternating current.

An excellent fact to keep in mind at all times is that **an alternating current circuit can at any particular instant be compared to a D. C. circuit.**

As we usually work with the effective values of current and voltage in A. C. circuits and can always consider the circuit during a certain period of one alternation, or as the current is flowing in only one direction for the moment, this greatly simplifies tracing the flow of current in the circuit and making any calculations with the current or voltage.

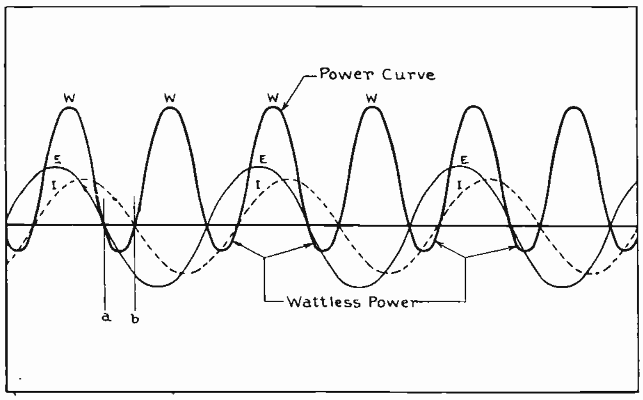

Fig. 13. Voltage, current, and power curves of a single-phase circuit in which the voltage and current are out of phase. The current, represented by the dotted curves, is shown lagging behind the voltage in this case.

13. INDUCTIVE REACTANCE, CAPACITY REACTANCE, and IMPEDANCE

We have already mentioned that in A. C. circuits there are always two other factors besides resistance which control the current flow, and these are **inductance** and **capacity.**

The effects or opposition offered by inductance and capacity to the current and voltage of an A. C. circuit, are known as **inductive reactance and capacity reactance.**

If resistance, inductive reactance, and capacity reactance all tend to control the current flow in A. C. circuits, we should be able to sum these all up together to get the total controlling effect on the current and thus simplify our calculations and problems. That is exactly what we can do.

The total opposition offered to the flow of current in an A. C. circuit, is called **impedance.** The impedance of an A. C. circuit therefore, compares with the resistance of a D. C. circuit.

The factors that make up the impedance can be illustrated in another way as shown in Fig. 14.

Impedance is here shown as being composed of the resistance and total reactance. The total reactance is then subdivided into its two classes, Inductive reactance and Capacity reactance.

The impedance and reactance of A. C. circuits are both measured in the unit ohm, to be comparable to the resistance in ohms.

The symbols used to indicate these very important factors of A. C. circuits are as follows:

Z = Total impedance in ohms
X = Total reactance in ohms
X_L = Inductive reactance in ohms
X_C = Capacity reactance in ohms
R = Resistance in ohms.

14. OHMS LAW FOR A. C. CIRCUITS

Now that we know the factors that control the flow of current in A. C. circuits and also that they can all be grouped into impedance in ohms, it is easy to see how Ohms law can be applied to an A. C. circuit by simply substituting the ohms of total impedance for the ohms resistance used in D. C. Ohms law.

From Ohms law for D. C. circuits we learned that the current flow could be determined by dividing the voltage by the resistance in ohms. Then for **A. C. circuits, the current can be determined by dividing the effective voltage by the impedance in ohms. Or,**

$$I = \frac{E}{Z}$$

And from this we can obtain by transposition the other two very convenient formulas:

$$Z = \frac{E}{I}, \text{ and } E = I \times Z$$

As inductance and capacity are such important factors in A. C. circuits, and are the cause of inductive reactance and capacity reactance, it will be well to learn more about them. In addition to offering opposition to the current and voltage, inductance and capacity also cause the current to be out of phase with the voltage in most A. C. circuits. For these reasons we will explain them in detail in the following paragraphs.

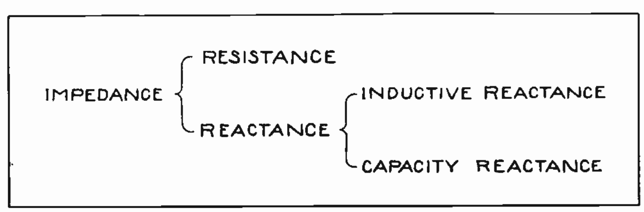

Fig. 14. This figure shows the several different factors which make up the impedance in an A. C. circuit.

15. INDUCTANCE

Inductance is that property or ability which an electric circuit possesses for developing a counter electro-motive force within the circuit itself, by electro-magnetic induction.

The counter-E. M. F. due to inductance is caused by the variations or changes of current strength in the circuit, and the corresponding changes or variations in the magnetic flux around it.

All A. C. circuits will have a certain amount of inductance. In some cases this inductance is so small that it can be disregarded entirely in ordinary problems; while in other cases the inductive effect is so great that the whole operation of the circuit or device may depend upon it.

Inductance tends to oppose every change of current that occurs in any circuit, by generating or inducing a counter-voltage of self-induction as the changing flux cuts across the conductors of the circuit itself.

For this reason, A. C. circuits which have coils or machine windings connected in them, have a much greater inductance than straight wires or lines, or incandescent lighting circuits. This is because coils and windings set up very strong fields of concentrated magnetic flux, and as these lines of force cut across the turns of the coil they generate considerable counter-voltage of self-induction.

A. C. circuits to which are connected induction motors and transformers are very highly inductive, because of the windings of these machines and their location on the iron cores of the device, in a manner which is ideal for establishing very strong magnetic fields.

Ordinary incandescent lighting circuits are considered as practically non-inductive because their inductance is so small that it is usually not considered in ordinary calculations.

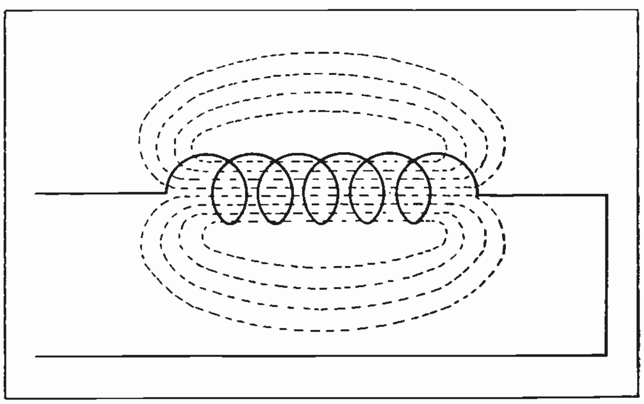

Fig. 15. The alternating flux around coils or wires of A. C. circuits produces voltage of self-induction and inductive reactance in the circuits.

The counter-voltage and inductive reactance which result from inductance in the winding of A. C. machines, regulates or limits the current flow a great deal more than the ohmic resistance does. This is the reason why many A. C. machines and devices will be burned out almost immediately if they are connected to a D. C. circuit of the same voltage.

The direct current, being constant in value, does not have a continually varying or moving flux to set up the counter-voltage of self-induction.

The unit with which we measure inductance in a circuit is called the **henry. A circuit has an inductance of one henry when a current change of one ampere per second will induce one volt counter-voltage of self-induction in that circuit.**

The unit "henry" is sometimes known as the **coefficient of self-induction,** and the symbol for this unit, "henry", is the capital letter L. Therefore, the expression 10 L means 10 "henrys" of inductance in the circuit.

Sometimes the inductance of a circuit is much less than one henry, and is expressed in milli-henrys (M. H.), or 1/1000 part of a henry.

16. COUNTER-VOLTAGE OF SELF-INDUCTION

Fig. 15 illustrates the manner in which the counter-voltage is build up by induction in a coil in an A. C. circuit. The current flowing through the coil sets up a strong magnetic field around all its turns.

We know that with alternating current these lines of force will be constantly expanding and contracting, and reversing in direction, as the current varies in amount and reverses in direction.

As the lines of force expand and contract, and cut across the turns of the coil in first one direction and then another, they will induce a **voltage which opposes the applied voltage.**

It will be well to keep this fact always in mind—**that the electro-magnetically induced currents are always in such a direction that the field set up by them tends to oppose or stop the force which produces them.** This is known as **Lenz's Law,** as it was disovered by an early experimenter named Lenz.

The manner in which the counter-voltage is set up by induction is illustrated more in detail in Fig. 16. In this figure we have shown a sectional view of a coil of wire as though the turns were all cut in half, lengthwise through the coil. The current set up by the applied line voltage at the particular instant, is shown flowing in at the lower conductor ends and out at the top ends.

The flux which will be set up by this current is shown around the lower end of the right-hand turn of the coil. Flux would, of course, be set up around all the turns but, for convenience in illustrating the principle of induction, is shown only around this one turn.

When the current of one alternation in the circuit builds up in the turns of the coil, the flux shown around the conductor or single turn will expand

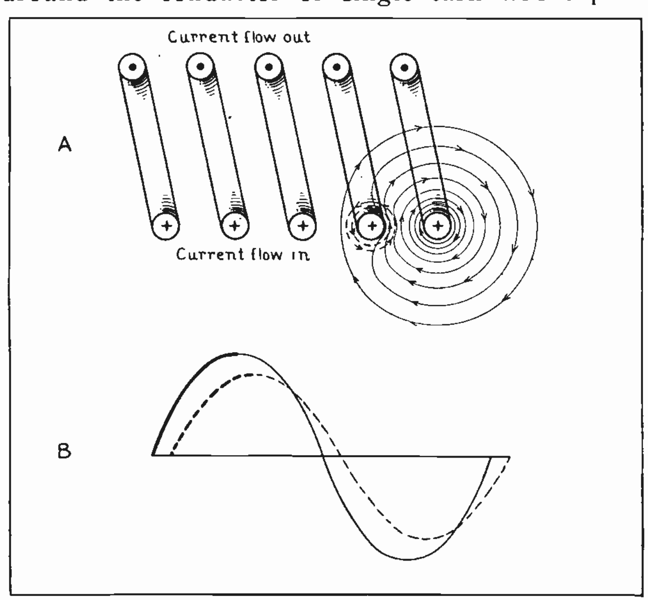

Fig. 16. The above diagram illustrates the manner in which the counter-voltage of self-induction is built up in an inductance coil.

more and more until the current reaches maximum value. During this building up of the current and flux, the lines will be cutting across adjacent turns of the coil in the direction shown, and will be inducing a voltage in them.

By applying the right-hand rule for induced voltages, we find that the direction of the voltage induced in the second turn of the coil, will be opposite to the applied voltage. This also checks with Lenz's law which says that the direction of the induced current will be such that its field will oppose the force that produces it.

When we consider that the flux of a coil in an A. C. circuit will be continually cutting across all turns of that coil, and that the counter-voltage it will induce in all these turns will add together as the turns are all in series, we can then see that the counter-voltage of self-induction in such a coil may greatly limit the flow of curent through it.

If we place an iron core in such a coil, and allow it to build up a much stronger field, this will greatly increase the inductance of the coil. Such coils are often called **choke coils** because of the "choking" or limiting effect which their counter-voltage has on the flow of alternating current through them.

A coil of several hundred turns wound on a large iron core and connected across a 110 or 220-volt, 60-cycle circuit, may produce nearly as much counter-voltage as the applied line voltage, and allow only a very small current to flow through the coil.

This explains why coils of A. C. devices or machines are usually wound with a much smaller number of turns than are D. C. devices for circuits of the same voltage; because on A. C. circuits the inductive reactance or counter-voltage controls the current even more than the ohmic resistance does.

This self-induced voltage caused by the inductance of a coil as shown in Fig. 16-A, being in a direction which opposes the applied line voltage, actually tends to make the current in the coil lag behind its voltage. That is, the current alternation does not reach its maximum value until a few degrees later than the voltage does, as shown by the curves in Fig. 16-B.

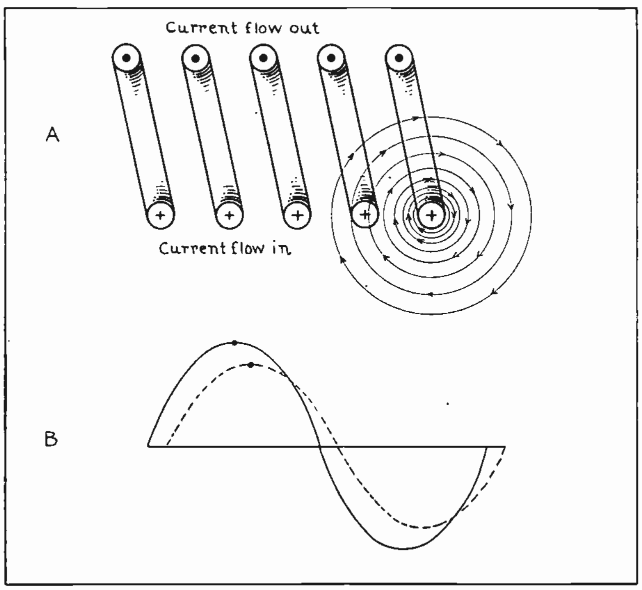

Fig. 17. This view shows the flux around one turn of a coil during the period when the current is at maximum value. The flux is neither contracting nor expanding at this period, and therefore produces no voltage of self-induction.

When the voltage of the alternation reaches maximum value, the current tends to stop increasing, but this causes the flux around the conductor to stop expanding and also to stop generating the counter-voltage in the turns of the coil. This allows the current to rise to its full maximum a little later than the voltage reaches its peak.

This is illustrated in Fig. 17-A, where the flux has stopped expanding and producing counter-voltage; and on the curves at "B" the current and voltage peaks are marked by the round dots.

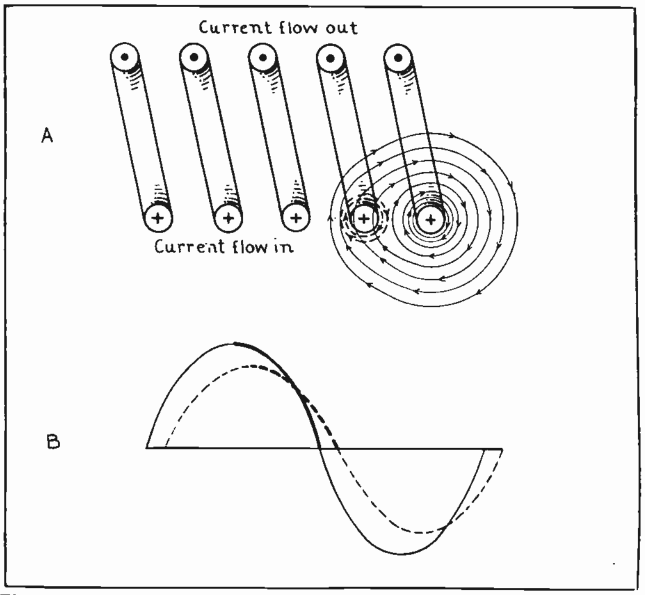

Fig. 18. This sketch shows the same coil as in Figs. 16 and 17 during a period when the current through the coils is decreasing from maximum to zero value. Note how the flux contracts and cuts across the turns of the coil.

As the voltage starts to reduce and causes the current to decrease, the lines of force around the turns of the coil will start to contract or die down as shown in Fig. 18-A. They are now cutting across the turns of the coil in the opposite direction to what they formerly were, and so they induce a voltage in the same direction as the applied voltage. This self-induced voltage now adds to, or aids, the applied voltage, which still further explains why the current flow reaches its maximum value after the voltage does.

As the voltage dies on down to zero and the current also tends to decrease to zero, the contracting lines of force keep on inducing voltage that tends to make the current continue in the same direction, even for a short instant after the applied voltage has reached zero.

Thus the current of the alternation reaches its zero value slightly later than the voltage does.

17. LAGGING CURRENT CAUSED BY INDUCTANCE

From these illustrations we can see that inductance causes the current to reach its maximum and zero values a few degrees later than the voltage, or to lag behind the voltage. Inductance, therefore, causes the current to be out of phase with the voltage. The greater the inductance of an A. C. circuit, the farther its current will lag behind the voltage.

In circuit diagrams inductance is usually represented by turns of a coil, as shown in Fig. 15.

In a circuit that has practically all inductance and very little resistance, the current would lag almost 90 degrees behind the applied voltage. If it were possible to have a circuit with all inductance and no resistance, the current lag in that circuit would then be 90°. This condition is, of course, not possible, because all circuits have some resistance.

Fig. 19 shows the curves for the applied voltage E, counter-voltage of self-induction Ec, current I, and flux F, for a circuit that we shall assume has inductance only and no resistance.

The change in current value and the corresponding flux change are much more rapid as the current passes its zero point. This can be seen by noting the various amounts of current change along the curve I, between the vertical time lines which divide the alternation into even time periods of 1/8 alternation each. You will note that the current change from "l" to "m" is much greater than in the next equal time period from "m" to "n".

This very rapid change of current and flux will cause the maximum counter-voltage to be induced at the time the current passes through its zero value. The curve Ec shows the counter-voltage at maximum during this period.

The current changes at the lowest rate when near its maximum value, or from "o" to "p", and "p" to "q". The correspondingly slower flux change at this point causes the induced counter-voltage to be at or near zero value during this period.

So we find that the counter-voltage of self-induction in this case lags behind the current by 90 degrees. The applied line voltage to overcome the counter-voltage is 180° out of phase with it, or in direct opposition to the counter-E. M. F.

The applied voltage therefore "leads" the current by 90°, or as we more commonly say, the current "lags" the voltage by 90°.

In actual circuits, the current would never lag this far but would be somewhere between this point and the "in phase" position, according to the amount of inductance in the circuit.

The curve E, which represents the applied voltage to overcome the voltage of self-induction, is shown 180° out of phase with the voltage of self-induction and 90° ahead of the current.

In any actual circuit the energy voltage would be a few degrees later than the voltage curve E in this figure, because there would be a little resistance to overcome.

The applied voltage in Fig. 19 is shown at zero value when the current is at maximum, while in an actual circuit having some resistance, the energy

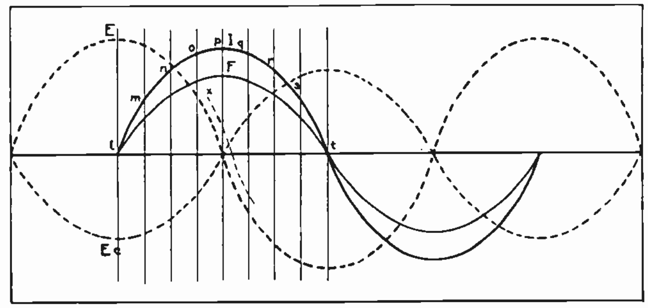

Fig. 19. Curves for a single-phase circuit in which the current and voltage are approximately 90° out of phase with each other, due to inductance in the circuit.

voltage would still be a little above the zero value, as shown by the short dotted section of the curve at "X".

18. SELF-INDUCTION IN D. C. CIRCUITS

While there is practically no inductive effect or counter-voltage of self-induction in a D. C. circuit as long as the current does not vary, there is often considerable voltage of self-induction set up in windings of large D. C. machines or magnets when the circuit is first closed or opened. This effect is encountered with the rotors or fields of large alternators, as their coils are excited by D. C.

When D. C. voltage is first applied to the field winding of large machines, it may actually require several seconds or more for the current to build up to its full value and overcome the effects of self-induced counter-voltage set up by the expanding flux.

When such circuits are opened, the sudden collapse of flux around the coils may induce very high voltage, which tends to oppose the decrease of current or keep the current flowing in the same direction. This accounts for the very severe arcs drawn when some highly-inductive D. C. circuits are opened.

The choking effect or counter-voltage of self-induction in an A. C. circuit will vary directly with the frequency of the current, or the rapidity with which the flux changes and reversals are made.

This fact is taken advantage of in constructing certain devices, such as choke coils for lightning arresters, load-limiting reactors, etc. These devices will be explained later.

19. CALCULATING INDUCTANCE AND INDUCTIVE REACTANCE

The amount of inductance which any coil or device may have in henrys can be calculated by the following formula:

$$L = \frac{\text{Maximum flux} \times \text{no. of turns}}{\text{Maximum current} \times 10^8}$$

In which:

10^8 = 100,000,000, or the no. of lines of force necessary to be cut in one second to produce one volt.

When the inductance of a certain device or circuit is stated or known in henrys, the inductive reactance in ohms can be found by the following formula:

$$X_L = 2\pi \times f \times L$$

In which:

X_L = inductive reactance in ohms
π = 3.1416, or ratio of circumference to diameter of a circle
2π = 6.2832
f = frequency in cycles per second
L = inductance in henrys

This formula is very important, as the inductive reactance is one of the factors we need to know in order to apply the A. C. ohms law for making any A. C. circuit calculations.

As most A. C. power circuits are highly inductive due to the machine windings, as previously explained, inductive reactance is the factor most commonly encountered in ordinary A. C. work in power plants and industrial plants.

Induction motors and transformers are highly inductive devices.

20. CAPACITY

In alternating current circuits there is always a certain amount of condenser effect, or tendency to store an electro-static charge as the varying voltage of each alternation is applied. This condenser effect is known as the **capacity** of a circuit.

You will recall, from an explanation of condensers in the Elementary Section of this set, that a condenser consists of two or more surfaces or areas of conducting material, separated by an insulator or dielectric. This condition exists in an electric circuit, as the wires form the conducting areas, and their insulation, or in some cases air only, forms the dielectric between them.

You have also learned in the earlier discussion of condensers that the amount of charge in coulombs which a condenser will absorb depends on the voltage applied.

On ordinary low-voltage A. C. circuits of short length, the condenser or capacity effect is so small that it need not be considered in every day problems. On high-voltage transmission lines of great lengths, the capacity effect is often very great and must be carefully considered in several ways.

For example, such lines may store such a charge that even after they are disconnected from the power plant they may hold a charge of thousands of volts and many kilowatts. In fact, they often hold so much of a charge for a short period after the voltage source has been disconnected from them, that the wires would be very dangerous to handle until after they have been shorted together or grounded by placing a ground wire across them. This discharges the capacity charge stored in the line and makes the wires safe to handle.

21. UNIT OF CAPACITY

Capacity of electric circuits or condensers is measured and expressed by the unit, **farad. A condenser has one farad capacity when a charge of one coulomb will raise the condenser potential one volt.**

The coulomb, you will recall, is a flow of one ampere for one second. A condenser of one farad capacity will take a charge of one coulomb when one volt is applied to its terminals.

Most condensers have capacities of only a few millionths of a farad; so the unit **micro-farad,** meaning $\frac{1}{1,000,000}$ of a farad, is much more commonly used than the larger unit.

Capacity is, however, always expressed in farads or fractions of a farad when used in calculations. For example, 50 microfarads would be expressed as .000,050 farad. The symbol for farads or capacity is the large letter "C".

22. CONDENSER CHARGING CURRENT

When voltage is first applied to the terminals of a condenser, as shown in Fig. 20, a current will at once start to flow into the condenser to store up its electro-static charge. If the direction of the applied voltage and current for the instant are as shown by the arrows in Fig. 20-A, the top plate of the condenser will become positively charged and the lower plate negatively charged, as shown.

When the voltage is first applied to a condenser and before its plates have had time to build up their charge of voltage, the current flow into the condenser will be very rapid and at maximum value, even though the applied voltage is still very low. This is illustrated by the curves in Fig. 20-B. The curve E represents the applied voltage; the curve I, the current flow to the condenser; and the dotted curve Ec, the counter-voltage of the condenser. These curves are shown for a circuit that has practically all capacity and very little resistance.

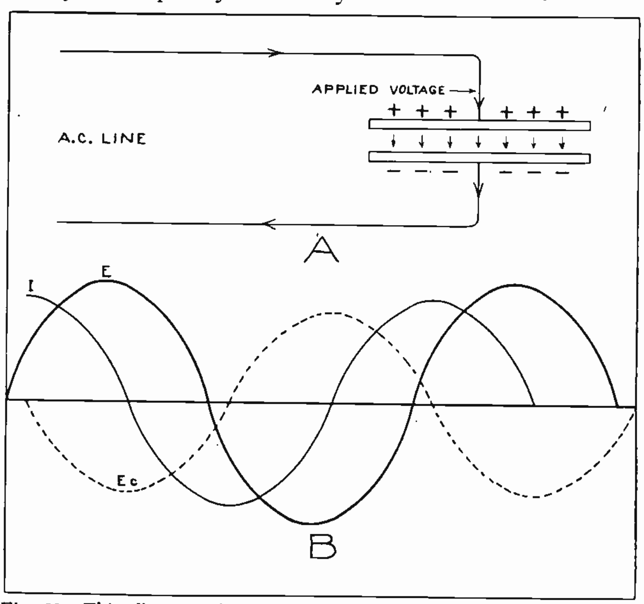

Fig. 20. This diagram shows the current leading the voltage by nearly 90°, due to capacity or condenser effect in the circuit.

You will note at the first curve on the left that the current reaches maximum value just a little later than the applied voltage starts from zero value. Then, as the applied voltage keeps on increasing, the counter-voltage, Ec, of the condenser is building up and reduces the flow of current, until it reaches zero value just after the applied voltage reaches maximum.

In this circuit, therefore, the current leads the voltage by nearly 90 degrees. If it were possible to have a circuit with all capacity and no resistance, the current would lead the voltage by 90°.

When the applied voltage passes its maximum value and starts to die down, the condenser starts to discharge, causing the current to start to flow in the reverse direction just after the applied voltage reaches maximum.

As the condenser discharges, its counter-voltage dies down as shown by the dotted curve Ec, until it reaches zero value just a few degrees later than the applied voltage does.

When the alternating voltage reverses, the current flows into the condenser in the opposite direction and charges its plates with opposite polarity.

In this manner a condenser receives its heaviest or maximum current just as the applied voltage reverses and starts to build up in a new alternation. and then the condenser discharges its current ahead of the next voltage reversal, causing the current in such a circuit to lead the voltage.

Current does not actually flow through a condenser as long as its insulation is not punctured by too high voltage, but the rapid flow of alternating current in and out of a condenser as it charges and discharges, provides a flow of current that can be measured by an ammeter or used to operate devices, just as though it actually flowed clear through the circuit.

The amount of the charging current is proportional to the size or capacity of the condenser, and is also proportional to the amount and frequency of the applied voltage.

When a condenser is connected in a high frequency circuit it will allow a much greater flow of current than when in a low frequency circuit.

Condensers in a D. C. circuit do not allow any current flow except during the first instant that the voltage is applied, and while the condenser is taking its charge. If a condenser which has been charged in this manner is short-circuited, it will discharge its energy in one violent rush of current.

23. CAPACITY REACTANCE

Capacity of an A. C. circuit causes **capacity reactance, or condensive reactance,** as it is often called. This condensive reactance tends to oppose the flow of current similarly to resistance and inductive reactance.

Capacity reactance tends to oppose any change in the voltage of a circuit, and causes the voltage to lag behind the current, as previously explained.

We learned that inductive reactance causes the current to lag behind the voltage; so we find that in this respect capacity reactance is opposite to inductive reactance.

Lagging voltage can also be expressed as "leading current", as both terms express the same condition in the circuit. In describing the phase relations of the voltage and current, we usually say "lagging current" or "leading current"; and seldom refer to lagging voltage.

When the capacity of any circuit is known in farads, the capacity reactance in ohms can be determined by the following formula:

$$Xc = \frac{1}{2\pi \times f \times C}$$

In which:

Xc = capacity reactance in ohms
f = frequency in cycles per sec.
C = capacity in farads
$2\pi = 6.2832$

This formula is very important, as we want to be able to convert the apparent resistance effect of capacity into ohms capacity reactance, in order to apply Ohms law to any A. C. circuit problems.

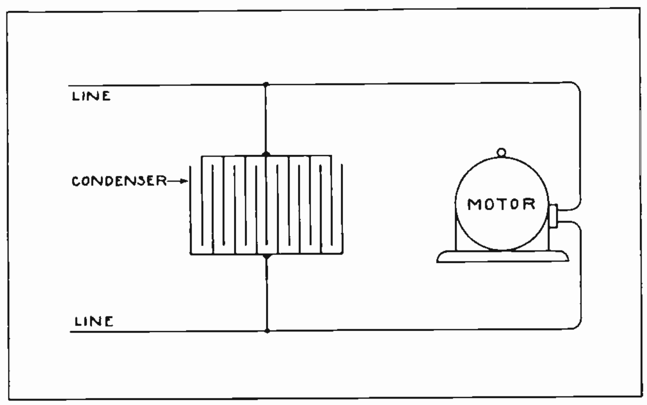

Fig. 21. A condenser connected in parallel with a motor will cause lagging voltage or leading current, and will neutralize effects of induction produced by the motor.

Capacity effect or condensers are usually shown in circuit diagrams by a symbol such as is used in Fig. 21. This symbol represents the plates of a condenser, the two groups of which are connected to the two wires of the circuit. In an actual condenser the insulation between the plates may be any convenient form of dielectric, such as fibre, glass, rubber, paper, or oil. In the case of A. C. circuits and lines, this insulation which forms the dielectric for the condenser effect may be the insulation on the wires or, as in the case of transmission lines, merely the air between the wires.

As capacity reactance is opposite in effect to inductive reactance, special condensers are often connected in A. C. circuits in industrial plants, to neutralize the effects of inductance and lagging current. The advantages of this will be explained later.

In Fig. 21 the condenser is connected in parallel with a motor. When the voltage of any alternation starts to build up on this circuit, the condenser takes a charge and its voltage opposes the building up of the applied energy voltage, thus causing it to lag.

When the energy voltage reaches maximum, the condenser will be fully charged and, as the energy voltage starts to decrease, the condenser voltage will then be applied to the circuit and will tend to oppose the dying down of the energy voltage, or will maintain it longer. This retards the dying down of the energy voltage and causes it to reach its zero value an instant later. After the energy voltage reaches zero the condenser will still be discharging or applying a little voltage to the circuit.

Thus we have another illustration of the manner in which a condenser causes the lagging voltage, or leading current as it is more frequently expressed.

The effects of capacity are very useful and valuable in many circuits.

Static condensers are often used on highly-inductive power circuits to improve the power factor by neutralizing the effect of excessive inductance.

Condensers are also used extensively in radio and telephone work to pass currents of certain frequencies and stop those of lower frequency or D. C. in various circuits.

24. SUMMARY OF INDUCTANCE AND CAPACITY

Some of the most important points to remember about inductance and are summed up briefly in the following:

Inductive equipment in A. C. circuits consists of coils, windings of transformers, motors, generators, choke coils of lightning arresters, current-limiting reactors, etc.

Capacity effects in A. C. circuits are produced by static condensers, over-excited synchronous motors, long transmission lines or underground cables, etc.

(a) Inductance opposes current changes; Capacity opposes voltage changes

(b) Inductance causes lagging current; Capacity causes leading current

(c) The effect of inductance is opposite to that of capacity, or their effects are 180° apart and tend to neutralize each other

(d) Excessive inductance is detrimental to the power-carrying capacity of a circuit; Excessive capacity is detrimental to the power-carrying capacity of a circuit

(e) Inductance may be used to neutralize the effect of excessive capacity; Capacity may be used to neutralize the effect of excessive inductance

(f) Inductance causes low power-factor, "lagging"; Capacity causes low power-factor, "leading"

(g) Lagging power-factor may be compensated for by static condensers or over-excited synchronous motors.

25. SERIES A. C. CIRCUITS

There are four classes of series circuits commonly encountered in alternating current work. These are as follows:

(a) Circuits with resistance only
(b) Circuits with resistance and inductive reactance
(c) Circuits with resistance and capacity reactance
(d) Circuits with resistance, inductive reactance, and capacity reactance.

Incandescent lighting circuits and those supplying similar non-inductive equipment are considered to have resistance only. Actually these circuits have a slight amount of inductance and capacity, but it is so small that it is negligible.

Circuits of this type can be treated similarly to D. C. circuits, because the resistance is the only opposing force to the current and therefore the resistance equals the total impedance. To determine the current flow in such circuits it is only necessary to divide the applied voltage by the resistance or impedance in ohms.

The most common types of circuits encountered in alternating current power work are those which have resistance and inductive reactance. The method of determining the impedance and currents of such circuits will be covered in the following paragraphs.

26. CALCULATION OF IMPEDANCE IN SERIES A. C. CIRCUITS

Fig. 22-A shows a resistance and an inductance connected in series. The resistance of 8 ohms is represented by the usual symbol, with which you are already familiar, and the inductive reactance of 6 ohms is represented by the coil symbol which is commonly used for showing inductance in circuits.

At first thought, it might seem that we can merely add the ohms resistance and ohms inductive reactance to get the total impedance in the circuit; because this was a method used in D. C. circuits with two or more resistances in series. This method cannot be used with resistance and inductive reactance, however, because their effects on the current are out of phase with each other.

If this circuit had only resistance, the current which would flow when alternating voltage is ap-

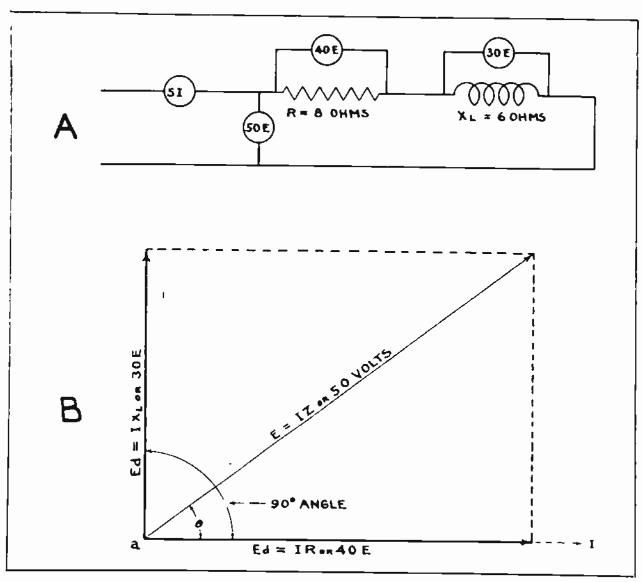

Fig. 22. "A". A resistance coil connected in series with an inductance coil in an A. C. circuit. "B". This sketch shows the method of determining the amount of impedance of the circuit shown at "A".

plied would be in phase with the voltage. If the circuit had only inductance, the current which would then flow would be 90° out of phase with the voltage, or lagging 90° behind it.

27. GRAPHIC SOLUTION FOR RESISTANCE AND INDUCTIVE REACTANCE IN SERIES

As the inductive reactance and resistance both tend to affect the flow of current and its phase position with respect to the voltage, we can determine these effects by the use of a diagram such as shown in Fig. 22-B. A current of 5 amperes is assumed to be flowing through circuit "A". In Fig. "B" we have a horizontal line used to represent the voltage drop Ed cross the 8 ohms resistance which is in phase with "I" and a vertical line at an angle of 90° with the horizontal line, to represent the voltage drop Ed across the 6 ohms inductive reactance.

These two lines can be drawn to scale, so that the length of each will represent the proper value in ohms. In diagrams of this type the lines are all considered to be revolving, like the spokes of a wheel, in a counter-clockwise direction around the point where they join at "a".

Keep this fact well in mind whenever examining or working with such diagrams.

If these lines are revolving counter-clockwise, then the shorter line representing the voltage drop across the inductive reactance X_L will be 90° ahead of the long line, which represents the Ed across "R".

As the current which flows through the resistance "R" would be in phase with the voltage drop across "R", the horizontal line can also be allowed to represent the current in phase with the voltage drop across "R".

If we now draw dotted lines as shown to complete the rectangle we will have what is known as a **parallelogram of forces**, and the length of the diagonal line "IZ" will indicate the total voltage drop across the circuit and its position with respect to the line "IR", will indicate the angle of phase difference between the current and the applied voltage.

If the lines representing the voltage drop across the resistance and inductive reactance are carefully drawn to scale (in this case 1/20" per volt) and at the proper angle, then by measuring the length of the line "IZ" we will get the total applied voltage. The line "IZ" will also represent the total impedance with the scale drawn to allow 1/4" per ohm.

This graphic method provides an exceedingly simple way of solving such problems. It would not, of course, be very accurate on large values or figures, because it would be difficult to make the lines long enough or to measure them with sufficient accuracy. This diagram will, however, show the manner in which the amount of current lag in degrees is determined by the proportion of resistance and inductive reactance in the circuit.

By examining the diagram in Fig. 22-B, or by drawing another like it with a longer line to represent a greater amount of inductive reactance, you can readily see that this would swing the diagonal line "IZ" farther upward, or would cause a greater angle of phase difference between the current and voltage.

On the other hand, if we were to increase the amount of resistance and lengthen the horizontal line, this would swing the diagonal line down and nearer to the resistance line, and bring the resulting current nearer in phase with the voltage.

28. FORMULA FOR IMPEDANCE OF RESISTANCE AND INDUCTIVE REACTANCE IN SERIES

The impedance of such a circuit, with resistance and inductive reactance in series, can be calculated accurately by the following formula:

$$Z = \sqrt{R^2 + X_L^2}$$

We can obtain the impedance in ohms by squaring the resistance and inductive reactance in ohms, adding these squares together, and then extracting the square root of the sum, as shown by this formula.

In the case of the circuit shown in Fig. 22, where we have 8 ohms resistance and 6 ohms inductive reactance, our problem would be:

$$Z = \sqrt{8^2 + 6^2}, \text{ or}$$

$$Z = \sqrt{64 + 36}, \text{ or}$$

$$Z = \sqrt{100}, \text{ or 10 ohms impedance}$$

This illustrates the various steps in solving such a problem with the exception of the details of finding the square root. If you require it you can obtain assistance on this process from your instructor.

It will be a very good plan to practice a few square root problems until you can handle these problems easily, because there are numerous opportunities in alternating current electric problems to use square root to excellent advantage.

On the great majority of ordinary electrical jobs it will not be necessary to use such problems; but, if you desire to work up to higher positions, you will want to be able to work out the problems pertaining to the various circuits and machines you may be operating.

29. RESISTANCE AND CAPACITY IN SERIES

Fig. 23-A shows a circuit in which a resistance and capacity are connected in series. The resistance of 4 ohms is represented by the usual symbol and the capacity reactance of 3 ohms is represented by the symbol for a condenser.

For the graphic solution of this problem we will again draw a horizontal line of proper length to represent the 4 ohms resistance, and a vertical line to represent the 3 ohms capacity reactance. This time, however, we will draw the vertical line 90° behind of the horizontal line which represents the resistance. The line is drawn in this position because we know that capacity reactance tends to make the current lead the voltage.

If the circuit were all capacity and no resistance, this lead would be 90°; but, as there are both resistance and capacity, we make the lines of proper length and space them 90° from each other, to determine what the angle of lead of the circuit will be.

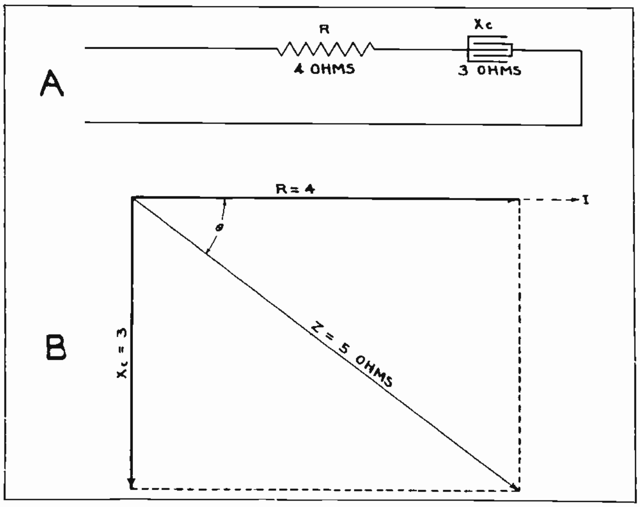

Fig. 23. "A". This circuit has a resistance connected in series with a condenser. "B". The vector diagram shows the method of determining the impedance and angle of lead between the current and voltage for a circuit such as shown at "A".

By again completing the parallelogram with dotted lines and drawing the diagonal line through it cornerwise, this line "Z" will represent the total impedance and will also show the phase position or angle of lead of the current. The lines in this figure are drawn to scale, using ½-inch per ohm, and you will find by measuring the line "Z" that it shows the total impedance to be 5 ohms.

This, of course, is not the sum of the two values 4 and 3, which would be obtained if they were added by arithmetic, but it is the correct vectorial sum of the two values when they are out of phase 90° as shown.

The impedance of the circuit shown in Fig. 23 can be calculated by the use of a formula very similar to that used for the circuit in Fig. 22. The formula is as follows:

$Z = \sqrt{R^2 + Xc^2}$, or, in this case

$Z = \sqrt{4^2 + 3^2}$, or

$Z = \sqrt{16 + 9}$, or

$Z = \sqrt{25}$, which gives 5 ohms impedance

30. RESISTANCE, CAPACITY, AND INDUCTANCE IN SERIES

Fig. 24-A shows a circuit in which we have resistance, inductance, and capacity all in series.

In Fig. 24-B, all three of these values are represented by the solid lines, R, Xc, and X_L. In this case we have again drawn a horizontal line to represent the resistance. The line X_L, representing inductive reactance, is drawn 90° ahead of the resistance line; and the line Xc, representing capacity reactance is drawn 90° behind the resistance line.

We know that inductive reactance and capacity reactance have opposite effects in the circuit and will therefore tend to neutralize each other. As the inductive reactance is the greater in this case, our first step will be to subtract the 10 ohms capacity reactance from the 22 ohms of inductive reactance.

This neutralizes or eliminates the 10 ohms capacity reactance and 10 ohms of the inductive reactance. The remaining 12 ohms of inductive reactance which are not neutralized by the capacity effect, and the resistance, will be the factors which determine the total impedance and the phase angle of the current.

Once more drawing our parallelogram with the remaining factors or values, we find that the current still lags behind the applied voltage and that the total impedance is 20 ohms. The scale to which the lines are drawn in this case is 1/16 of an inch per ohm.

The total impedance of a circuit such as shown in Fig. 24-A can be more accurately calculated by means of the formula:

$Z = \sqrt{R^2 + (X_L - Xc)^2}$

In this case $X_L - Xc$ is 22 − 10, or 12.

Then, $12^2 = 144$.

The next step indicated by the formula is to square the resistance. This will be 16 × 16, or 256.

Then, 256 + 144 = 400.

And the final solution of the problem will be:

$Z = \sqrt{400}$, or 20 ohms.

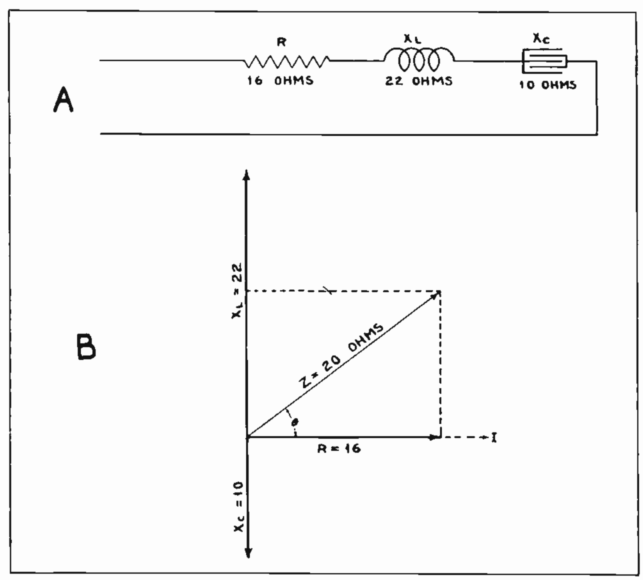

Fig. 24. "A". Resistance, inductance, and capacity connected in series in an A. C. circuit. "B". Note how the capacity reactance is subtracted from the inductive reactance, as the two neutralize each other in the circuit.

31. PARALLEL A. C. CIRCUITS

Parallel alternating current circuits are of the same four general types as series circuits. That is, they may contain resistance only, resistance and inductance in parallel, resistance and capacity in parallel, or resistance, inductance, and capacity in parallel.

To determine the impedance of parallel A. C. circuits we must use the reciprocal method, somewhat similar to that which was explained for parallel resistances in D. C. circuits.

You will recall that with D. C. circuits when the resistances were in series we added the resistance in ohms of all the circuits to obtain the total resistance. But when resistances were in parallel we first added the conductances or reciprocals of the resistance to obtain the total conductance, and then inverted this or obtained its reciprocal, which is the total resistance.

This is the same general method used in determining the total impedance of parallel A. C. circuits.

The opposite of impedance in A. C. circuits is the **admittance.** Admittance in this case means the same as conductance in D. C. circuits. Admittance is, therefore, always the reciprocal of the impedance and is expressed in **mhos,** the same as conductance for D. C. circuits.

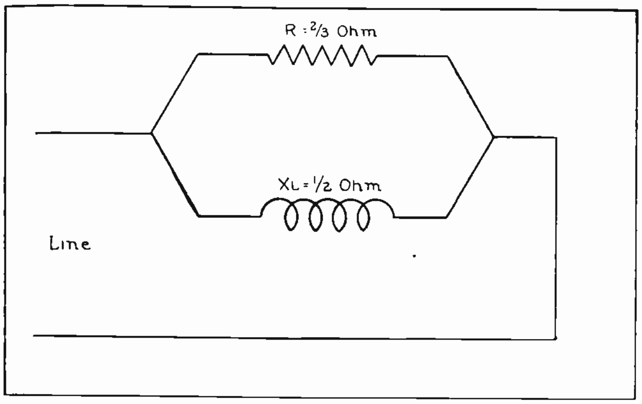

Fig. 25. Resistance and inductance in parallel. The impedance for this circuit can be determined by the formulas given on this page.

32. RESISTANCE AND INDUCTANCE IN PARALLEL

Fig. 25 shows a resistance of ⅔ ohm connected in parallel with an inductive reactance of ½ ohm. The total impedance of this circuit can be determined by the following formula:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_L}\right)^2}}$$

According to this formula we must first obtain the separate reciprocals of the resistance and inductance by dividing the number 1 by each of these values in ohms. These reciprocals are then squared and added together and the square root of their sum next obtained. The final step is to obtain the reciprocal of this square root by dividing the number 1 by it, as shown by the formula.

Using with the formula the values given in Fig. 25, the problem becomes:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{\frac{2}{3}}\right)^2 + \left(\frac{1}{\frac{1}{2}}\right)^2}}$$

Here we have substituted the $\frac{2}{3}$ ohm resistance for the "R" shown in the formula, and the $\frac{1}{2}$ ohm inductive reactance for the X_L shown in the formula.

We next divide the number one by each of these values, to obtain their reciprocals, and our problem then becomes:

$$Z = \frac{1}{\sqrt{\left(\frac{3}{2}\right)^2 + 2^2}}$$

Then by squaring these reciprocals as indicated by the formula, the problem becomes:

$$Z = \frac{1}{\sqrt{\frac{9}{4} + 4}}$$

Before we can add $\frac{9}{4}$ and 4, they must both be converted to like fractions, or:

$$Z = \frac{1}{\sqrt{\frac{9}{4} + \frac{16}{4}}} \text{ or } \frac{1}{\sqrt{\frac{25}{4}}}$$

Then obtaining the square root of $\frac{25}{4}$, our problem is reduced to $\frac{1}{\frac{5}{2}}$,

We then divide 1 by $\frac{5}{2}$ to get the reciprocal, which equals $\frac{2}{5}$ ohms, total impedance.

18. RESISTANCE AND CAPACITY IN PARALLEL

Fig. 26 shows a circuit with a resistance of $\frac{1}{4}$ ohm and a capacity reactance of $\frac{1}{3}$ ohm, connected in parallel. The total impedance of this circuit can be determined by a formula similar to the one just used, or as follows:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{X_C}\right)^2}}$$

Substituting the values given for the circuit, the problem becomes:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{\frac{1}{4}}\right)^2 + \left(\frac{1}{\frac{1}{3}}\right)^2}}$$

When we divide the figure 1, in each case, by the resistance and reactance to get their reciprocals, we then have:

$$Z = \frac{1}{\sqrt{4^2 + 3^2}} \text{ or, } \frac{1}{\sqrt{16 + 9}}$$

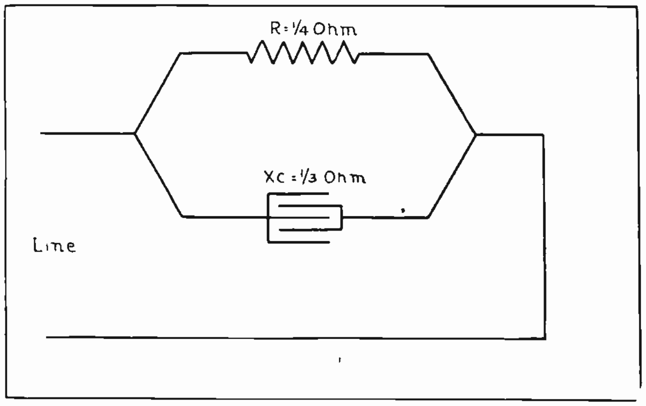

Fig. 26. Resistance and capacity in parallel in an A. C. circuit. Practice using the formulas given on these pages for determining the impedance of such circuits.

As 16 + 9 = 25, the problem now remains:

$$Z = \frac{1}{\sqrt{25}}$$

The square root of 25 = 5, so this reduces the problem to:

$Z = \frac{1}{5}$, or $\frac{1}{5}$ ohm impedance

19. RESISTANCE, INDUCTANCE, and CAPACITY IN PARALLEL

Fig. 27 shows a circuit with inductance, resistance, and capacity in parallel.

The total impedance of this circuit can be found by the formula:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{R}\right)^2 + \left(\frac{1}{Xc} - \frac{1}{XL}\right)^2}}$$

Note the similarity between this formula and the one which was used for impedance of series circuits having inductance, resistance, and capacity. The principal difference is merely that with parallel circuits we use the reciprocals of the values, instead of the values in ohms themselves.

You will also note that with parallel circuit problems we subtract the reciprocal of the inductive reactance from the reciprocal of the capacity reactance, as one of these effects tends to neutralize the other, as they did in series circuits.

In the circuit shown in Fig. 27 the inductive reactance in ohms is larger than the capacity reactance, but when the reciprocals of these values are obtained their relative sizes will be reversed, as shown by their subtraction in the formula.

In a circuit where the capacity reactance might be the greatest, we would reverse the order of subtraction, in order to subtract whichever reciprocal is smallest from the one that is largest.

Substituting the values from the circuit in Fig. 27, for the symbols given in the formula, the problem of determining the total impedance becomes:

$$Z = \frac{1}{\sqrt{\left(\frac{1}{1\frac{1}{3}}\right)^2 + \left(\frac{1}{\frac{3}{5}} - \frac{1}{1\frac{1}{2}}\right)^2}}$$

Our first step will be to convert the whole numbers and fractions, to fractions, as follows;

$$1\frac{1}{3} = \frac{4}{3}, \text{ and } 1\tfrac{1}{2} = \frac{3}{2},$$

$$\text{Then } Z = \frac{1}{\left(\frac{1}{\frac{4}{3}}\right)^2 + \left(\frac{1}{\frac{3}{5}} - \frac{1}{\frac{3}{2}}\right)^2}$$

Then by dividing 1 by each of the fractions to obtain their reciprocals we have:

$$Z = \frac{1}{\left(\frac{3}{4}\right)^2 + \left(\frac{5}{3} - \frac{2}{3}\right)^2}$$

Next subtracting $\frac{2}{3}$ from $\frac{5}{3}$ as shown in the latter part of the formula, we have:

$$Z = \frac{1}{\left(\frac{3}{4}\right)^2 + \left(\frac{3}{3}\right)^2} \text{ or } Z = \frac{1}{\left(\frac{3}{4}\right)^2 + 1^2}$$

Then $\frac{3}{4}$ squared equals $\frac{9}{16}$, and 1 squared equals 1, So, $Z = \dfrac{1}{\sqrt{\frac{9}{16} + 1}}$, or $Z = \dfrac{1}{\sqrt{\frac{25}{16}}}$

Obtaining the square root of $\frac{25}{16}$ gives $\frac{5}{4}$,

So, $Z = \dfrac{1}{\frac{5}{4}}$, or $\frac{4}{5}$ ohm impedance

Once more let us remind you that on your first electrical jobs you may not have much use for problems or formulas such as the foregoing. But as you may wish to be able to calculate the impedance of A. C. circuits at some future date, these problems have been worked out step by step in these pages to provide a guide or reference for you, in case you need them in the future.

Working them out carefully and also applying these formulas to other similar circuit problems will be very good practice, and will also help you to more clearly understand certain points about impedance, admittance, and reactance in A. C. circuits.

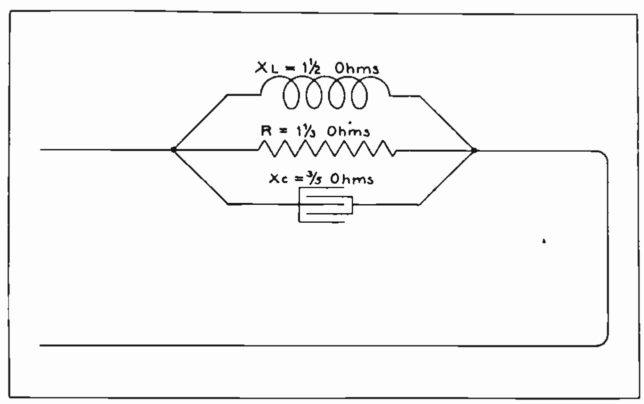

Fig. 27. This sketch shows inductance, resistance, and capacity connected in parallel. The method of determining the impedance of such a circuit is thoroughly explained on this page.

35. CURRENT IN PARALLEL CIRCUITS

The total line current or resultant current as it is called, and also the amount of lag or lead of the current in parallel A. C. circuits, can be worked out by the use of vector diagrams such as those shown in Figs. 22, 23 and 24 for series circuits.

When using vector diagrams for parallel circuits, the lines can be allowed to represent the currents through the resistance, inductance, and capacity branches of the circuit.

The current through the separate branches of the circuit, or the devices which contain the resistance, inductance, and capacity, can be determined by the use of an A. C. ammeter, or by the use of Ohms law formulas for each branch, as follows:

$$I = \frac{E}{R},\ I = \frac{E}{X_L},\ I = \frac{E}{X_C},\ \text{etc.}$$

For example, in Fig. 28 is shown a circuit with resistance, inductance, and capacity in parallel. We can assume that these are a heater resistance, a transformer winding, and a condenser all operated from the same 40-volt line. Separate tests made with an ammeter in the circuit of each device show 8 amperes flowing through the resistance or heater, 4 amperes through the inductance or transformer coil, and 2 amperes in the condenser circuit.

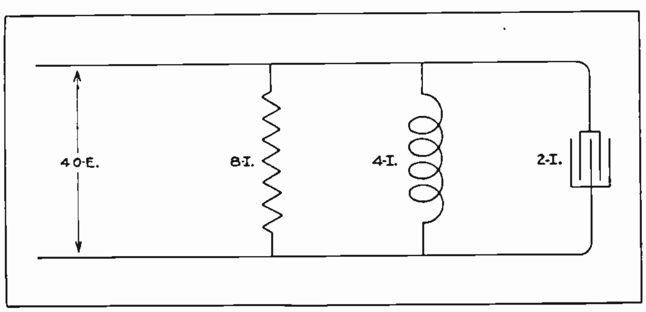

Fig. 28. Note the amount of current in each of the branches of the above circuit and compare this sketch with Fig. 29, while determining the total current in the circuit.

By use of Ohms law formulas, we can determine the resistance and reactance in ohms of each of these devices as follows:

$$R = \frac{E}{I} \text{ or } R = \frac{40}{8}, \text{ or 5 ohms}$$

$$X_L = \frac{E}{I} \text{ or } X_L = \frac{40}{4}, \text{ or 10 ohms}$$

$$X_C = \frac{E}{I} \text{ or } X_C = \frac{40}{2}, \text{ or 20 ohms}$$

We can represent the currents of this circuit by the vector diagram shown in Fig. 29.

The solid horizontal line represents the current through the resistance; and as this current will be in phase with the line voltage, this same line can represent the phase position of the voltage.

The vertical line, which is 90° behind the horizontal current and voltage line, represents the current through the inductance.

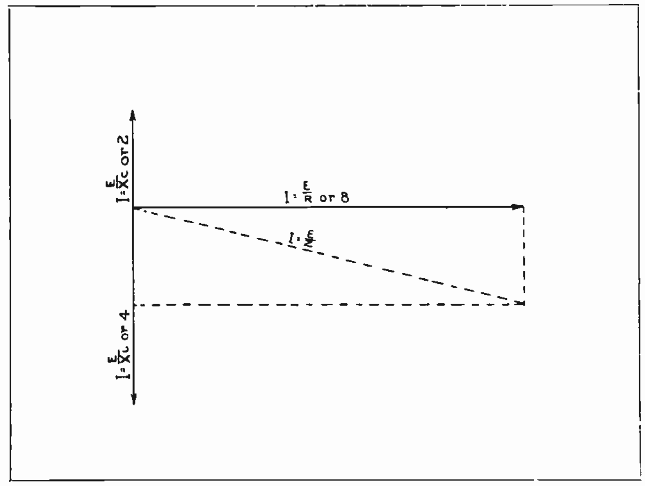

Fig. 29. This diagram illustrates the method of determining the current in parallel A. C. circuits which have all three factors; resistance, inductance, and capacity.

The shortest vertical line, which is 90° ahead of the horizontal line, represents the current through the condenser.

Now if we subtract the leading current from the lagging current, and draw dotted lines to form the parallelogram with the remaining lagging current and the current which is in phase with the voltage, the diagonal line, $I = \frac{E}{Z}$, through this parallelogram will represent the total line current.

It may seem peculiar that the total line current or vectorial sum of the three currents is only slightly more than the current through the resistance. This is due to the fact that the leading and lagging currents, which are balanced, tend to neutralize each other, or actually circulate between the condenser and inductance in Fig. 28, and do not flow on the line wires from the generator. This interesting fact will be further discussed later in a section on power factor.

36. POWER FACTOR

We have learned so far in our study of alternating current and A. C. circuits, that inductive reactance and capacity reactance often cause the current in these circuits to be out of phase with the voltage.

We have also found that this reduces the amount of effective or **true power** in watts and causes a certain amount of wattless energy. This was illustrated by the voltage, current, and power curves shown in Fig. 13.

In a D. C. circuit the power in watts can always be obtained by multiplying the volts by the amperes. It can also be obtained with a wattmeter. When the current and voltage of an A. C. circuit are in phase with each other the power can be determined by the same method as used for D. C. circuits. That is, by obtaining the product of the volts and amperes.

37. TRUE POWER AND APPARENT POWER

When the voltage and current of an A. C. circuit are out of phase their product will not give the **true power** in the circuit, but instead gives us what we call **apparent power.** The apparent power of A. C. circuits is commonly expressed in **kilovolt amperes,** abbreviated kv-a.

Alternators, transformers, and certain other A. C. machines are commonly rated in kv-a. When an A. C. wattmeter is connected in a circuit which has lagging or leading current it will read the **true power** and not the apparent power. This is due to the fact that the coils which operate the pointer in the meter depend upon true or effective power for their torque which moves the pointer against the action of the spring.

It is very important to remember that you can always obtain the true power of an A. C. circuit by means of a wattmeter. The product of voltmeter and ammeter readings in the circuit will give the apparent power, and this figure will usually be more than the true power, because the current in most A. C. circuits lags somewhat behind the voltage.

Keep in mind that true power is expressed in watts and kilowatts and apparent power in volt-amperes or kilovolt-amperes.

38. POWER FACTOR DEFINITION AND FORMULA

The ratio between the apparent power and true power in any circuit is known as the power factor of that circuit. This power factor is expressed in percentage and can always be found by dividing the true power by the apparent power, or this can be expressed as a formula in the following manner:

$$\text{Power Factor} = \frac{\text{True power}}{\text{Apparent power}}$$

The practical man, doing electrical maintenance work or power plant operating in the field, is likely to have many occasions to use this formula and method of determining the power factor of various machines or circuits with which he is dealing. Therefore, it is well to keep in mind that you can always determine the apparent power of a circuit or machine by means of a voltmeter and ammeter and obtaining the product of their readings; then obtain the true power by means of a wattmeter, and finally determine the power factor by means of the formula just stated.

If the apparent power in kv-a. is known for any circuit or machine, and the power factor of that circuit or machine is also known, then the true power can be determined by the following formula:

$$\text{True Power} = \text{App. power} \times \text{P. F.}$$

As many A. C. machines are rated in kv-a. and have their power factor stated on the name-plate, this formula will often be very handy for determining the amount of true power the machine will supply.

In case the true power and the power factor of a circuit are known, the apparent power can be determined without the aid of meters by the following formula:

$$\text{Apparent Power} = \frac{\text{true power}}{\text{P. F.}}$$

The greater the angle of phase difference between the current and voltage in an A. C. circuit, the less true power will be obtained and the lower will be the power factor. Therefore we find that power factor will always depend upon the amount of lag or lead of the current.

39. LAGGING OR LEADING CURRENT

Tests show that the power factor is mathematically equal to what is called the **cosine** of the angle of lag or lead between the voltage and current. When the voltage and current are exactly in phase this angle is zero, and its cosine and the power factor will then be 100%.

This condition is often called **unity power factor.** As the voltage and current get out of step or out of phase, the power factor starts to drop below 100%, and the greater the angle of phase difference becomes the lower the power factor will drop.

When the angle of phase difference is 90° either lagging or leading, the power factor will be zero, and, regardless of the amount of voltage or the amount of current flowing, there will be no true power developed.

A lag or lead of 90° is not encountered in electrical circuits, because there is always a certain amount of resistance, and no circuit is entirely made up of inductance or capacity.

The term "angle of phase difference" which will be used considerably from now on is represented by the symbol $\ominus$ or $\emptyset$.

40. CAUSES OF LOW POWER FACTOR

As previously mentioned, the majority of A. C. circuits possess considerable inductance. Therefore, we usually find lagging current on most power circuits in the field.

Lightly loaded A. C. power equipment, such as motors, alternators, and transformers have much lower power factor than fully loaded machines. For this reason idle or lightly loaded A. C. machines should be avoided as much as possible, and all such equipment kept operating as nearly at full load as possible.

A great number of factories and industrial plants, using large amounts of A. C. equipment, fail to realize the importance of power factor and of having machines of the proper size and type so that they can be kept operating fully loaded. This results in low power factor on their circuits, and in the overheating of conductors and machines by the excessive currents set up by wattless power. This condition provides a splendid field of opportunity for the trained electrical maintenance man who has a knowledge of power factor, and the ability to measure the power required for various loads and select suitable motors and other equipment to handle these loads in the most efficient manner.

In many cases hundreds of dollars per month can be saved on power bills, machines and circuits relieved of current overloads, and frequent damage to windings prevented, by simply correcting the power factor in the plant. A great many untrained electrical men have little or no real conception of this subject and its importance. So you will find it very well worthwhile to carefully study and obtain a good understanding of these principles, and of the methods for correcting power factor, which will be covered later.

41. EXAMPLES OF LOW POWER FACTOR

The following problems, which are very typical of conditions often encountered in the field, should help you to more fully understand and appreciate this material given on power factor.

Let us suppose that on a certain job you have measured a circuit with a voltmeter and ammeter, and found 30 amperes flowing at 220 volts. Multiplying these two figures gives us 6600 watts of apparent power. A wattmeter connected in this same circuit shows a reading of only 3960 watts true power, which indicates that the power factor is rather low.

By the use of the formula:

$$\frac{\text{true power}}{\text{app. power}} = \text{power factor}$$

which, in this case would be $\frac{3960}{6600} = .60$ P.F., it is easy to see that a great deal of the current which is flowing in this circuit is not producing effective power.

If the company in whose plant this condition exists is generating its own power, the generators may be overloaded and overheated by wattless current, which doesn't produce power at the motors or equipment.

In case the power is being purchased from some generating company, we should keep in mind that these concerns very often give lower power rates if the consumer's power factor is kept up to a certain value. In other cases the customer may be charged a penalty rate for having low power factor.

Therefore it is often good economy to change the motors which are causing the low power factor, or to install power factor corrective equipment, such as synchronous motors or static condensers.

These devices provide condenser or capacity effects which neutralize the effects of induction motors and transformers, and thereby prevent excessive lagging current on the line and generators.

A. C. machines are commonly rated in kv-a., or kilovolt amperes, because the heating effect in their windings is proportional to the square of the current in amperes which these windings are caused to carry.

If these machines were rated in kw. and the power factor was exceedingly low, they might be forced to carry more current than their windings could stand, in an attempt to produce the proper amount of true power in kw.

This is exactly what happens in a number of cases in various plants, where there are no trained electricians who understand or appreciate the importance of power factor, and the necessity for measuring the current in amperes as well as the watts or kw. shown by the wattmeters.

Suppose that in another case there is a transformer in the plant where you are employed, and this transformer is rated at 10 kv-a. and connected to a 500-volt line. A wattmeter in the circuit of the transformer shows the load to be only 9 kw., but the transformer continually operates at a rather high temperature, as though its windings might be overloaded.

An ammeter could be used to determine the current flow, but in this case let us assume that the test is made by a portable power factor indicator, and that it shows the power factor to be 75%.

If we check up on these figures with the formula previously given for apparent power, it will soon show why the transformer is operating above normal temperature.

In the first place a 10 kv-a. transformer designed to operate on 440 volts would have a current capacity of about 22.7 amperes. This could be proven in the following manner.

10 kv-a. is equal to 10,000 volt-amperes or apparent watts.

Then, according to the formula $\frac{W}{E} = I$, from Watts law, we find that in this case there would be:

$$\frac{10{,}000}{440} \text{ or } 22.7 + \text{ amperes,}$$

full load current for the transformer.

The actual load on the transformer we have found is 9 kw. at 75% P.F. 9 kw. $\div$ .75 = 12 kv-a. apparent power.

Then, as 12 kv-a. is equal to 12,000 apparent watts, the current for this load can be determined as follows:

$$\frac{W}{E} = I, \text{ or } \frac{12{,}000}{440} = 27.3 \text{ amperes.}$$

This shows that the transformer is carrying 5.6 amperes more than its full rated load, or is about 20% overloaded. This is not an excessive overload and would probably not cause any damage if the transformer is well ventilated and the load not left on too long.

This 10 kv-a. transformer would be fully loaded under each of the several following conditions.

10 kw. output at 100% P.F.
9 kw. output at 90% P.F.
8 kw. output at 80% P.F.
7 kw. output at 70% P.F., etc.

42. POWER IN SINGLE-PHASE CIRCUITS

Thus far we have only mentioned power in single-phase circuits.

With balanced polyphase circuits the power of the system will be the product of the power in one phase multiplied by the number of phases.

If the power is considerably unbalanced in the several phases, it should be calculated separately for each phase, and the power of the separate phases is then added together to get the total power on the system.

The apparent power in a single-phase circuit is determined by the usual Watts Law formula:

$$\text{App. W} = \text{E} \times \text{I}$$

The true power in kw. for a single-phase circuit is found by the formula:

$$\text{True W} = \text{E} \times \text{I} \times \text{P. F.}$$

When the apparent power, or kv-a., and the voltage of a single-phase circuit are known, the current can be determined as follows:

$$\frac{\text{App. W}}{\text{E}} = \text{I}$$

43. POWER IN TWO-PHASE CIRCUITS

In balanced two-phase circuits, the power is calculated the same as for two single-phase circuits, that is, by the formulas:

$$\text{App. W} = 2 \times \text{E} \times \text{I}$$
$$\text{True W} = 2 \times \text{E} \times \text{I} \times \text{P. F.}$$

To determine the current in either phase of a balanced two-phase circuit when the voltage and total kv-a. are known, use the formula:

$$\frac{\text{App. W}}{2 \times \text{E}}$$

Two-phase power is used very little at present, but you may occasionally encounter some older installations of this type which are still in use.

44. POWER IN THREE-PHASE CIRCUITS

The power of balanced three-phase circuits can be determined by the formulas:

$$\text{App. W} = \text{E} \times \text{I} \times 1.732$$
$$\text{True W} = \text{E} \times \text{I} \times 1.732 \times \text{P. F.}$$

These formulas will apply to any balanced three-phase circuit, whether it is connected star or delta.

The constant 1.732 is used in three-phase formulas because the power of one phase of a three-phase circuit is always:

$$\text{App. W.} = \frac{\text{E} \times \text{I}}{1.732}$$

This is due to the fact that in delta-connected systems the line current is always 1.732 times the phase-winding current of any device on the system; and in star-connected systems the line voltage is always 1.732 times the phase-winding voltage.

Therefore, part of the current in any line wire of a three-phase, delta circuit is not effective in producing power in that phase, but is used in the other phases; and part of the voltage between any two line wires of a three-phase, star system is effective in producing power in more than one phase.

So the apparent power in any one phase will always be:

$$\frac{\text{E} \times \text{I}}{1.732}$$

To obtain the power for all these phases we would then use the formula:

$$\text{Total 3-ph. app. W} = \frac{3 \times \text{E} \times \text{I}}{1.732}$$

However, as 1.732 is also the square root of 3, it is not necessary to multiply the single-phase power by 3 and then divide by 1.732, as the same result is obtained if we simply multiply the single-phase power by 1.732, as shown in the first two formulas given for three-phase power.

These two formulas are well worth memorizing, as you will have frequent use for them in any work with three-phase power circuits or machines, and you can always depend upon them to quickly and easily determine the apparent power or true power.

To get the true power always use the formula which includes the power factor.

45. CURRENT IN THREE-PHASE CIRCUITS

To determine the current of any phase of a balanced three-phase circuit, when the apparent power in kv-a. and the voltage are known, the following formula can be used:

$$\text{I} = \frac{\text{App. W}}{1.732 \times \text{E}}$$

When the voltage, true power in watts and power factor are known, the current can be determined as follows:

$$\text{I} = \frac{\text{True W}}{1.732 \times \text{E} \times \text{P. F.}}$$

To determine the voltage when apparent power and amperes are known:

$$\text{E} = \frac{\text{App. W}}{1.732 \times \text{I}}$$

To determine the voltage when true power and amperes are known:

$$\text{E} = \frac{\text{True W}}{1.732 \times \text{I} \times \text{P. F.}}$$

The voltage and current can also be determined with voltmeter and ammeter, when they are available. Check these formulas by actual meter tests while you are in the A. C. Department of your shop course.

46. PRACTICAL FIELD PROBLEMS

What will be the true power of a balanced three-phase circuit which has 20 amperes flowing at 440 volts, and at 80 per cent P. F.?

Using the formula:

$$\text{True power} = 1.732 \times \text{E} \times \text{I} \times \text{P. F.}$$

our problem becomes:

$440 \times 20 \times 1.732 \times .80$

$440 \times 20 = 8800$

$8800 \times 1.732 = 15241.6$ apparent power

$15241.6 \times .80 = 12193.28$ true watts

The apparent power in kv-a. will then be:

$\frac{15241.6}{1000}$, or 15.24 kv-a.

The true power in kw. will be:

$\frac{12193.28}{1000}$, or 12.2 — kw.

Suppose that in another case you have made a meter test on the circuit to a 65 h. p., three-phase induction motor. The voltmeter shows 230 volts across any one of the three phases, and an ammeter connected first in one phase and then the others, shows that the load is properly balanced and that 85 amperes is flowing in each wire. What is the apparent power of this circuit in kv-a?

Using the formula:

$$3 \text{ Ph. App. W.} = E \times I \times 1.732$$

We find that E × I = 230 × 85, or 19,550

Then 19,550 × 1.732 = 33,860.6 watts, and 33,860.6 ÷ 1000 = 33.86+ kv-a.

Testing this same circuit with a wattmeter, we find only 20,320 watts or 20.32 kw. of true power in the circuit.

Assuming that both the voltmeter and ammeter test and the wattmeter tests were made at the same time, and while the motor was operating under the normal mechanical load which it drives, what is the power factor of the circuit?

$$\text{P. F.} = \frac{\text{true power}}{\text{apparent power}}$$

or, in this case,

$$\text{P. F.} = \frac{20.32}{33.86} \text{ or } .60 + \text{P.F.}$$

This is a very low and undesirable power factor, and if we check the motor input in h. p., we will find the probable cause of the low power factor.

The motor is rated at 65 h. p., but is consuming only 20.32 kw. of true power when running with its normal connected load. As 1 kw. is equal to 1.34 h. p., then 20.32 × 1.34 = 27.2+ h. p., and this is less than half of the motor's full rating.

Lightly-loaded induction motors operate at a much lower P. F. than fully loaded ones, and are common causes of low power factor.

In cases such as the one in this problem, if the mechanical load on the motor is never more than 27.2 h. p. and not particularly difficult to start, the 65 h. p. motor should be changed to one of about 27 or 30 h. p., to obtain better P. F. and higher efficiency.

If the total true power in a balanced, 440-volt, three-phase system is 125 kw., and this system is operating at 90 per cent. power factor, what will be the current in each phase?

Referring back to the formula given for finding current in a 3 Ph. circuit, when the true power, power factor, and voltage are known, we find that:

$$I = \frac{\text{True watts}}{1.732 \times E \times \text{P. F.}}, \text{ or}$$

in this case, 125 kw. = 125,000 true watts; therefore

$$I = \frac{125{,}000}{1.732 \times 440 \times .90}, \text{ or } 182.2+ \text{ amperes.}$$

Work out this problem and prove the figures. Practice working problems with the formulas given in this section until you are quite familiar with their use and the manner in which the power factor affects such calculations on actual circuits and machines which you will encounter in your work.

POWER MEASUREMENT

In the preceding articles we have mentioned several times the use of meters to measure the voltage, current, or power of A. C. circuits.

It is very important that you appreciate the great value of meters in such work, and also that you know how to properly connect and use them. This fact was emphasized in the section on Direct Current and it is equally as important, or even more so, in connection with A. C. circuits and machines.

The intelligent use of the proper meters often helps to improve the efficiency of operation of various power machines, and also prevents damage to equipment by making sure that the voltage and current are right for the design and rating of that equipment.

In many cases very great savings can be effected by permanently connecting the proper meters to certain heavy power circuits or the circuits of individual machines, to allow frequent observation of voltage, load, and power factor conditions.

Frequently the saving effected in this manner will more than pay for the cost of the meters, in the first few months of their use.

On circuits where no meters are permanently installed, it is well to make periodic tests with portable meters, to see that the machines or circuits are operating at proper voltage, and that they are not overloaded. These tests will also show if certain machines are operating lightly loaded and causing low power factor and poor efficiency.

Many of the values for A. C. circuits can be easily calculated when certain others are known, by the use of the formulas which have been given in the preceding articles. In other cases, it may be much quicker and easier to use meters to determine these values. By using meters where necessary or most convenient, and the simple formulas where meter readings are not obtainable, practically any problem can easily be solved.

47. CONNECTING INSTRUMENTS

When making any tests with portable meters or when installing permanent meters, it is very important to get all connections properly made. Otherwise, incorrect readings will be obtained, and wrong connections may result in damage to the instruments, or danger to the person making the connections.

With A. C. voltmeters, ammeters, and wattmeters also, the same general rule applies as was given for

D. C. meters: **always connect voltmeters and potential elements of wattmeters across the line, and always connect ammeters and current elements of wattmeters in series with the line — never in parallel.**

The coils or shunts of ammeters and of the current elements of wattmeters are of so low resistance that if they were connected across the line, a short circuit would result and probably burn out the instrument. In such cases there is also danger of the operator being burned by flying drops of molten copper, or of his getting "flashed eyes" from the blinding flash of the arc which may be caused by the short circuit, when wrong connections are made to live circuits.

The following connection diagram and instructions for the use of meters on various tests are given to enable you to make such tests correctly and safely.

48. POWER MEASUREMENT ON SINGLE-PHASE CIRCUITS

Fig. 31 shows the proper connections for a voltmeter, an ammeter, and a wattmeter in a single-phase circuit. Note that the voltmeter and potential coil of the wattmeter are both connected **across** the line; and that the ammeter and the current coil of the wattmeter are both connected **in series** with the line.

It does not matter which side of the line the ammeter and wattmeter are connected in, as all the current to the motor must flow through each line wire, and correct total readings can be obtained from either wire.

The voltmeter in this case will indicate whether or not the line voltage is proper for the voltage rating of the motor as given on the name-plate of the machine.

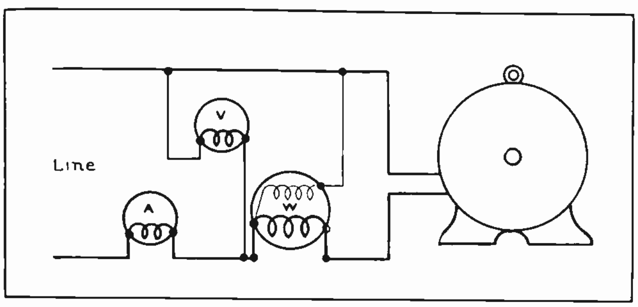

Fig. 31. This sketch shows the method of connecting the meters to measure voltage, current, and power of a single-phase motor.

Too low a voltage will cause reduced torque and poor efficiency of motors, and possibly also cause them to overheat.

The ammeter when connected as in Fig. 31 will indicate the current load on the motor and show whether the machine is overloaded, or possibly too lightly loaded. The full-load current rating of A. C. motors is usually stamped on their name-plates.

The wattmeter may be used instead of the ammeter to determine the load on the machine; but if the power factor is low, the wattmeter reading divided by the voltage is not a reliable indication of the current load on the machine; because with low power factor there may be considerable wattless current flowing.

The wattmeter can be used with the voltmeter and ammeter to determine the power factor of the machine. The wattmeter will read the true power, and the product of the voltmeter and ammeter readings will give the apparent power. Then, dividing the true power by apparent power will give the power factor, as previously explained.

The wattmeter reading gives the true power input to the motor, and enables one to calculate the h. p. the motor should deliver if it is operating properly.

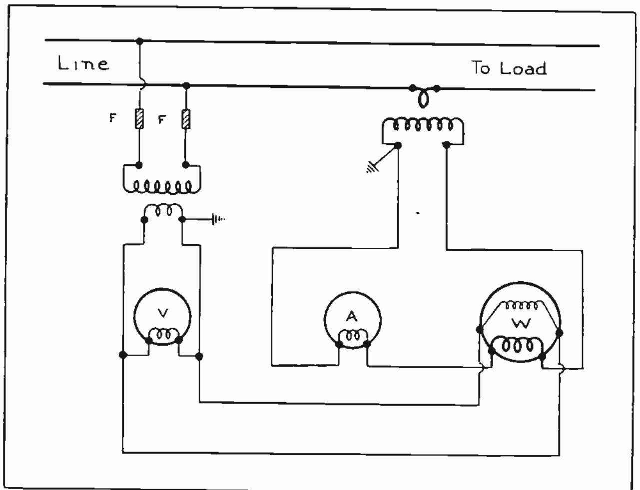

Fig. 32. When meters are used to measure the energy of high voltage lines instrument transformers are used to reduce the voltage and current to the meters.

49. METER CONNECTIONS FOR HIGH VOLTAGE CIRCUITS

Fig. 32 shows the meters and connections for measuring the voltage, current, and power of a high-voltage circuit, where **instrument transformers** are used.

On circuits over 600 volts, meters are very seldom connected directly to the line, because of the danger to operators and the difficulty and expense of insulating the meter elements for the higher voltages.

Special transformers are used to reduce the voltage and current at the meters to a definite fraction of the voltage and current on the line. These transformers are called **current transformers** and **potential transformers,** and are designed to maintain on their secondaries a fixed ratio of the voltage or current on their primaries. The meters used with such transformers can, therefore, be calibrated to read the full voltage, current, or power on the line.

The potential transformer on the left in Fig. 32, has its primary winding connected across the line, and its secondary supplies both the voltmeter and the potential coil of the wattmeter, which are connected in parallel.

The current transformer on the right has its primary coil connected in series with the line, and its secondary supplies both the ammeter and the current coil of the wattmeter, which are connected in series.

You will note that the secondaries of both transformers are grounded, to prevent damage to instruments and danger to operators in case the insulation between the high-voltage primary and the low-voltage secondary coils should fail.

The potential transformer is equipped with fuses in its primary leads.

Never disconnect an ammeter from a current transformer without first short-circuiting the secondary coil of the transformer.

If the secondary of a current transformer is left open while its primary is connected to the line, dangerously high voltages may be built up in the secondary. This will be more fully explained in a later section on transformers.

50. DETERMINING RESISTANCE OF A. C. CIRCUITS

Resistance measurements on A. C. circuits can be made by use of a Wheatstone bridge or a megger, both of which were explained in the section on D. C. meters. The Wheatstone bridge is most frequently used for making accurate tests on lines or devices of various resistances, although the megger is very convenient for making tests where extreme accuracy is not required.

The resistance of an A. C. circuit or device can also be calculated from voltmeter and ammeter readings, by passing low-voltage direct current through the circuit under test. Inductance does not oppose the flow of D. C., so the current flow will be proportional to the voltage and resistance only.

When the voltage and current readings are obtained with D. C. meters and with D. C. voltage applied to the circuit, the resistance can then be determined by the formula $E \div I = R$, with which you are already familiar.

It is well to remember that the resistance of wires and metallic circuits of copper, aluminum, iron, etc., will increase with any increase in the temperature of the conductors. This is particularly true of iron or resistance alloys in rheostats, and of the filaments in incandescent lamps.

The resistance of lamp filaments when heated to incandescence may be from 4 to 10 times as high as it is at 70° F., or ordinary room temperature.

51. CURRENT MEASUREMENTS ON THREE-PHASE CIRCUITS

Fig. 33 shows a three-phase motor with an ammeter connected in one of its phase wires to measure the current. If the motor is operating properly, the current should be very nearly the same, or balanced in all three phases. Prove this by actual tests on some of the motors in the A. C. Department of your shop course.

The current rating on the name-plate of any three-phase motor is the amount of current that should flow in each of the three wires leading to the motor. Therefore, if the motor shown in Fig. 33 has a name-plate rating of 50 amperes, an ammeter should

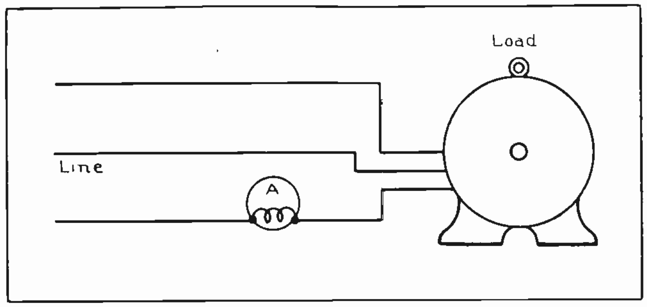

Fig. 33. Ammeter connected to measure the current in one phase of a three-phase motor.

show 50 amperes in any of the three phases when the motor is operating fully loaded.

If the current is unbalanced to any great extent, it indicates that there is probably a fault in one or more of the phases in the motor winding.

Where the current of a three-phase system is known to be balanced at all times, one ammeter permanently connected in any phase is all that is required to determine the current.

It is well, however, to occasionally test all three phases with a portable ammeter, to locate any possible unbalance which may occur due to faulty machine windings; or to locate unbalance which may occur on main wires by connecting more single-phase equipment on some one phase than on another.

All single-phase load connected to a three-phase system should be kept balanced as much as possible, by connecting an equal number of devices or equal loads in kv-a. to each phase.

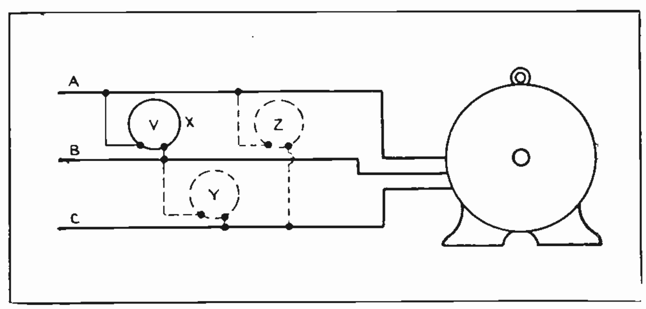

Fig. 34. This diagram shows three different connections for a voltmeter used to measure the voltage of each phase of the three-phase line to this motor.

Where the load is likely to be unbalanced and the amount of load on the different phases is varying, it is often well to have three ammeters, one connected in each phase.

52. VOLTAGE MEASUREMENTS ON THREE-PHASE CIRCUITS

Fig. 34 shows the method of connecting a voltmeter to indicate the voltage of a three-phase system or motor. The voltmeter can be connected between any two of the three wires, and should show approximately the same reading on all phases.

Slight variations of voltage between the various phases generally do no harm, but if the voltmeter shows widely varying readings when connected first at X, then at Y, and then at Z, it indicates that the circuit is probably unbalanced.

This unbalance and reduced voltage on certain phases will decrease the torque and efficiency of three-phase motors operating on the line.

53. POWER MEASUREMENTS ON THREE-PHASE CIRCUITS

For measuring the power of three-phase circuits, either single-phase or polyphase wattmeters can be used. The readings of single-phase wattmeters can be totalled up to obtain the three-phase power, while a three-phase wattmeter will read directly the true power of all three phases.

Where single-phase wattmeters are used, the two **wattmeter method** shown in Fig. 36 is very commonly applied.

In order to obtain correct results with the two meters, it is necessary to test them to make sure that corresponding coil leads are brought out to the same meter terminals; or, if they are not, to get them correctly marked so that the meters can be connected properly to the three-phase wires to get the right polarity of the meter coils.

To test the meters, connect them both to a single-phase circuit, or to the same phase of a three-phase circuit, as shown in Fig. 35-A. Make sure that there is some load on the circuit to enable the meters to show a reading.

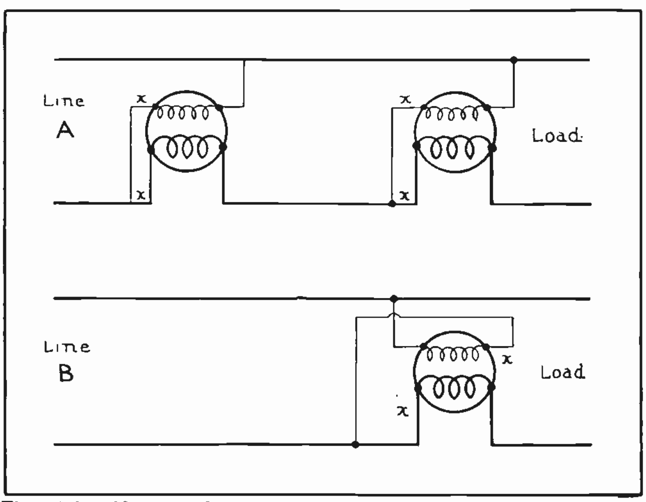

Fig. 35-A. Above is shown the method of connecting wattmeters to a single-phase circuit to locate the proper terminals of the potential and current coils.
Fig. 35-B. This sketch illustrates the method of reversing the leads to the potential coil if necessary, to make the meter read properly.

If both meters give the same indication with their pointers moving across the scale in the right direction, then carefully mark or tag the terminal of the potential coil and the terminal of the current coil which are connected together and to the line. In this figure these leads are each shown marked with an "X".

If one of the meters reads "backwards" when connected as shown in Fig. 35-A, the potential coil leads should be reversed as shown in Fig. 35-B. The meter should then read "forward"; that is, its pointer should swing to the right across the scale. The terminals or leads should then be marked as shown.

With the two meters now connected to the three-phase circuit as shown in Fig. 36 and with the proper terminals connected together and to the lines, the meter readings will be called **"positive" readings**. The sum of the two meter readings will be the total three-phase power of the circuit. If the meters are properly connected as shown in Fig. 36 and the pointer of one meter attempts to swing backwards, or below zero, the potential leads of that meter should be reversed, as shown on meter No. 2 in Fig. 37. Its reading is then called **"negative,"** and should be subtracted from that of the positive meter to get the three-phase power.

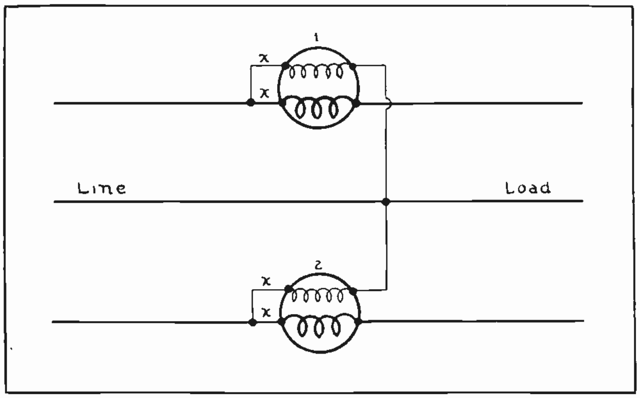

Fig. 36. This sketch shows the connections for using two single-phase wattmeters to measure the power in a three-phase circuit.

54. CORRECT CONNECTIONS NECESSARY FOR ACCURATE RESULTS

Fig. 38 also shows the connections for the "two wattmeter method" but shows the current coil of one of the meters connected in a different phase from what it was in Fig. 36. The current coils of the two wattmeters can be connected in any two of the three phases, and if the potential coil leads are properly connected the results should be the same. However, one of the potential coil leads of meter No. 2 is connected wrong in Fig. 38, as this connection will give correct readings only when the power factor is unity, or 100%.

As unity power factor is seldom found on any A. C. circuit, this connection should usually be avoided, and the potential coil lead should be connected as shown by the dotted line.

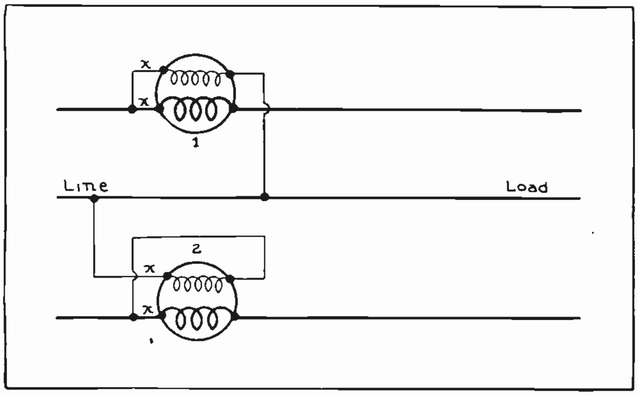

Fig. 37. This diagram shows the connections to the lower wattmeter reversed to obtain proper readings on circuits with low power factor.

When the "two wattmeter method" is used, the ends of the potential coils which are not attached directly to the same wire with their current coils should connect to the phase wire in which no current coil is connected; as shown in Fig. 36, or in Fig. 38 after the one lead is corrected as shown by the dotted line.

It may at first seem peculiar that two wattmeters used in this manner will give the total three-phase power of the circuit. This is true, however, because the current which flows to the lead through the unmetered wire at any instant must be flowing back to the alternator through one or both of the other wires, thus allowing the two meters to read full 3 Ø power.

The phase relations between the currents and voltages of a balanced three-phase system are such that the "two wattmeter method" will accurately give the total three-phase power, if the connections are properly made and the readings are added if they are both "positive", or subtracted if one is "negative" and the other "positive".

If wattmeter No. 1 in Fig. 36 reads 8000 watts and meter No. 2 reads 6000 watts, the total power will be 8000 + 6000, or 14,000 watts.

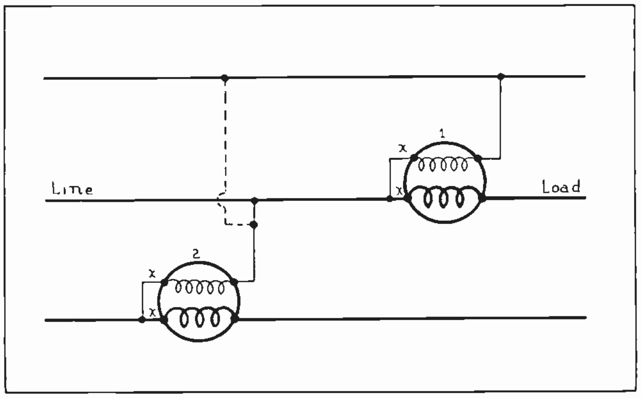

Fig. 38. This sketch shows the correct and incorrect methods of connecting one of the wattmeters when measuring three-phase power by the "two wattmeter method".

If the meters must be connected as shown in Fig. 37 to obtain readings above zero, then the negative reading must be subtracted from the positive reading to get the total power.

For example, if meter No. 1 in Fig. 37 reads 20,000 watts and meter No. 2 reads 6,000 watts, then the total power will be:

20,000 — 6,000, or 14,000 watts.

In all circuits where the power factor is less than 50 per cent., one of the two wattmeters will give a negative reading.

On circuits where the load is quite constant, one wattmeter can be used to determine the three-phase power, by connecting it first in one phase and then in another, as shown at positions 1 and 2 in Fig. 39.

The reading of the meter in position 1 is noted, and the meter is then shifted to position 2, and the reading is again noted. If both readings are "positive", their sum will give the total true power. If

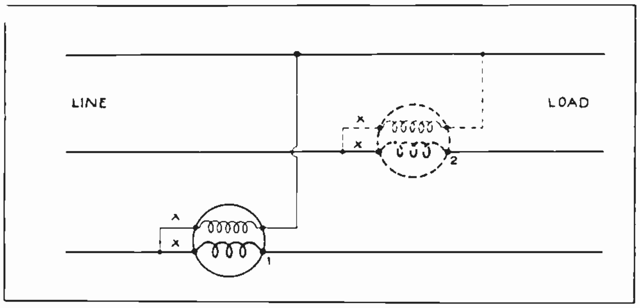

Fig. 39. The above diagram shows the manner of connecting one wattmeter in two different phases of a three-phase system in order to measure the total power.

one reading is "positive" and one negative, their difference will give the total true power.

One wattmeter should not be used to determine total three-phase power on circuits where the load varies much, as the load may change while the meter connections are being changed, and thus give an incorrect total.

55. POWER MEASUREMENT ON HIGH VOLTAGE CIRCUITS

Fig. 40 shows the connections for the "two wattmeter method" of measuring three-phase power on high-voltage circuits where instrument transformers are used.

Separate potential transformers supply the voltage from the two phases to the potential elements of the wattmeters. Separate current transformers supply the proportional current from the two phases to the current elements of the two wattmeters.

The same procedure of marking the potential and current coil leads and checking the positive or negative readings is followed in this case as when no instrument transformers are used.

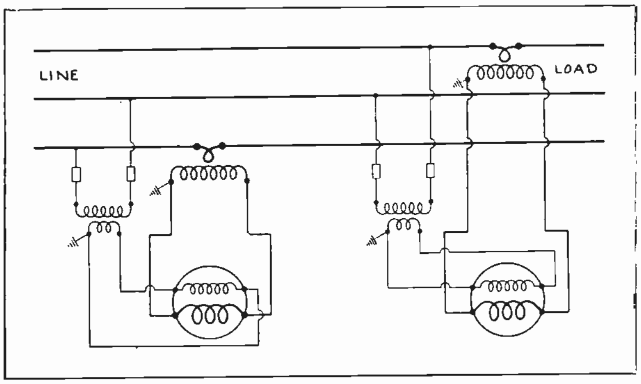

Fig. 40. Connections for two wattmeters on a three-phase circuit, using instrument transformers to reduce the voltage and current to the meters.

56. THREE METER METHOD OF POWER MEASUREMENT

Fig. 41 shows three wattmeters used to measure the total power of a three-phase system.

With this connection we use a **"Y box"** which consists of three separate resistances, connected together at one end to form a star connection and provide a neutral point to which one end of each wattmeter potential coil is connected.

When connected in this way, each wattmeter measures only the power of the phase in which it is connected, and the total power will be the sum of the three meter readings.

For example, if meter No. 1 reads 14,000 watts, meter No. 2 reads 16,000 watts, and meter No. 3 reads 17,000 watts; the total power will be 47,000 watts.

Wattmeters connected in this manner will always read "positive" regardless of the power factor.

This makes the method very simple and reliable and one which is very commonly used on large power circuits, where very accurate readings are important and all chance of error should be avoided.

For measuring the total power of a three-phase, four-wire system, the connections shown in Fig. 42 are used. In these systems the neutral wire is already provided by the fourth wire which is connected to the star point of the windings of the alternator or at the transformer connections, and therefor no Y box is needed.

The total power of the three-phase, four-wire system thus measured will be the sum of the three meter readings.

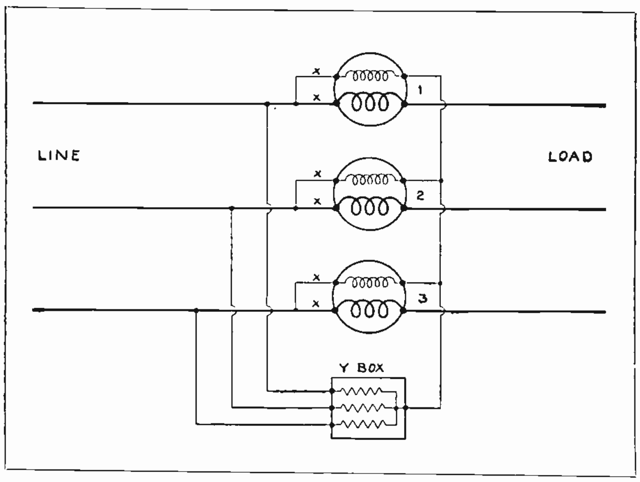

Fig. 41. Meter connections for a "three wattmeter method" for measuring the total power in a three-phase circuit. The Y Box shown in this diagram is explained in the accompanying paragraphs.

57. METERING THE OUTPUT OF AN ALTERNATOR

Fig. 43 shows the meters and connections for measuring the power output of an alternator, both in true power and apparent power, and also for determining the voltage, current, and power factor.

We will assume that the meter readings are as follows:

Voltmeter = 440 E
Ammeter = 60 I
Wattmeter No. 1 = 18,250 W
Wattmeter No. 2 = 21,750 W

The total three-phase true power will then be 18,250 + 21,750 = 40,000 W, or 40 kw.

The total three-phase apparent power will be E × I × 1.732, or 440 × 60 × 1.732 = 45,724.8 watts or approximately 45.725 kv-a.

The power factor will then be $\frac{\text{true power}}{\text{app. power}}$ or, 40 ÷ 45.725 = .874, or 87.4% P.F.

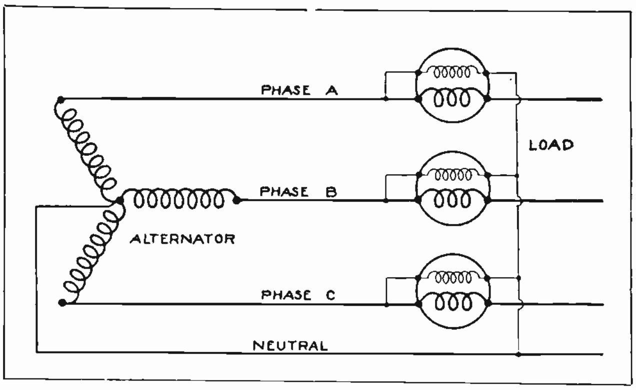

Fig. 42. This diagram shows the connections for three wattmeters to measure the power of a three-phase, four-wire system.

58. PRACTICAL METER TEST AND POWER PROBLEMS

The following practical examples are given for your practice, to make you thoroughly familiar with the use of the formulas and methods commonly used on actual circuits in the field.

In a great many cases the men who can make these calculations as well as operate and maintain the machines intelligently are the men who become foremen or chief operators.

Assume that we have made a meter test of a single-phase circuit and have obtained the following readings:

Voltmeter = 220 E
Ammeter = 80 I
Wattmeter = 14,000 W

What will be the kw., kv-a., and P.F. of this circuit?

Use the proper formulas in each case, looking them up in the preceding articles if necessary, and work out each part of the problem step by step, and carefully.

The answers are given here to enable you to check your results.

kw. = 14, kv-a. = 17.6, and P.F. = 79.5%

In another case, you are called upon to make a test of an alternator and you obtain the following meter readings:

Voltmeter = 2200 E
Ammeter = 50 I
Wattmeter = 160,000 W

What will be the kw., kv-a., and P.F.?

Answers: kw. = 160, kv-a. = 190.5+, and P.F. = .839 or 84−%.

On a two-phase system we find a voltage of 200 E on each phase, current of 60 I on each phase, and a wattmeter reading shows 9,000 watts on each phase. What will be the kw., kv-a., and P.F.?

Answers: kw. = 18, kv-a. = 24, and P.F. = .75

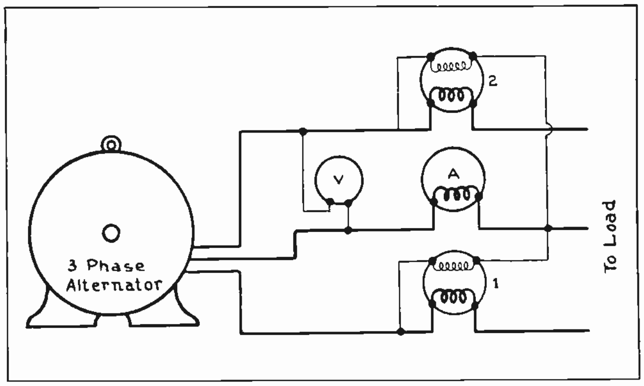

Fig. 43. Voltmeter, ammeter, and wattmeter connected to measure the voltage, current, and power output of a three-phase alternator.

If a coil or winding of an A. C. machine has a flow of 5 amperes through it when connected to 200 E, A.C., and has 20 amperes through it when connected to 100 E, D.C., what will be the impedance, the resistance, and the P.F. of the winding?

On A. C. circuits:

$$Z = \frac{E}{I}, \text{ therefore } \frac{200}{5} = 40 \text{ ohms impedance}$$

On D. C. circuits:

$$R = \frac{E}{I}, \text{ therefore } \frac{100}{20} = 5 \text{ ohms resistance}$$

When both the resistance and impedance are known,

$$P.F. = \frac{R}{Z}, \text{ therefore } \frac{5}{40} = \frac{1}{8} = \text{—, or } .125,$$

or 12½% P.F.

If a circuit with a condenser or capacity effect, causing a capacity reactance of 20 ohms, is connected in series with a resistance of 12 ohms, what is the total impedance and the P.F ?

$$Z = \sqrt{R^2 + Xc^2}, \text{ or } Z = \sqrt{12^2 + 20^2}$$

$$12^2 = 12 \times 12 \text{ or } 144$$

$$20^2 = 20 \times 20 \text{ or } 400$$

$$144 + 400 = 544$$

$$\sqrt{544} = 23.3 +, \text{ ohms impedance}$$

$$P.F. = \frac{R}{Z}, \text{ or } \frac{12}{23.3} = .515, \text{ or } 51.5\% \text{ P. F.}$$

COYNE Electrical School

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ESTABLISHED 1899

ALTERNATING CURRENT
AND
A. C. POWER MACHINERY

Section Two

A. C. Meters

Types, Construction, Operating Principles

Voltmeters, Ammeters, Wattmeters

Watthour Meters

Demand Indicators, Power Factor Meters

Frequency Meters, Synchroscopes

ALTERNATING CURRENT METERS

Alternating current meters are in many respects very similar to direct current meters, which were explained in the D. C. Section Two.

Ordinary A. C. meters consist of: The moving element, which is delicately balanced and mounted in jeweled bearings and has the pointer or needle attached to it; a controlling force or spring to limit the movement of the pointer and movable element; a stationary coil or element to set up a magnetic field; a damping vane or element to prevent vibration or excessive "throw" of the pointer; and the meter scale and case.

One of the principal differences between A. C. meters and D. C. meters is that, while certain types of D. C. meters use permanent magnets for providing the field in which the moving element rotates, A. C. meters use coils instead.

Some types of A. C. meters, also, operate on the induction principle, which is not used in D. C. meters.

59. TYPES OF A. C. METERS

There are several different types of A. C. meters each of which uses different principles to obtain the torque for moving the pointer. Some of the most common of these types are: The moving-iron repulsion type; inclined coil and moving vane type; dynamometer type; induction type; and hot-wire type.

Some types of A. C. meters can also be used on D. C. circuits with fair results, but they are usually not as accurate on D. C.

60. MOVING IRON TYPE INSTRUMENTS

The moving-iron principle used in some makes of A. C. voltmeters and ammeters is illustrated by the several views in Fig. 44. This is one of the simplest principles used in any type of alternating current meter, and is based upon the repulsion of two soft pieces of iron when they are magnetized with like polarity.

If two pieces of soft iron are suspended by pieces of string within a coil, as shown in the upper left-hand view of Fig. 44, and current is passed through this coil, the flux set up within the turns will magnetize the two parallel pieces of iron with like poles at each end. The repulsion of like poles will cause the two iron strips to push apart, as shown in the top center view. This effect will be produced with either D. C. or A. C. flowing in the coil, because it makes no difference if the poles of the iron strips do reverse, as long as like poles are always created together at the top and bottom ends of each strip.

The view at the upper right shows the poles reversed, and the strips still repel as before. They must, of course, be made of soft iron so their polarity can reverse rapidly with the reversal of the A. C.

Now, if the two iron strips are again suspended in a horizontal coil, as shown in the lower left view, and one of the strips is in this case rigidly attached to the side of the coil and the other suspended by a string so that it is free to move, the strips will again repel each other or push apart when current is passed through the coil, as shown in the lower center view.

The view at the lower right shows how this principle can be applied to move the pointer of the meter. One small piece of soft iron is attached to the coil in a fixed position as shown. The other piece is attached to the movable element or pointer, which is mounted on a shaft and pivots, so it is free to move.

When alternating current is passed through the coil, the two iron vanes are magnetized with like poles, and the repulsion set up between them causes the movable one to rotate in a clockwise direction and move the pointer across the scale.

61. A. C. VOLTMETERS AND AMMETERS

This principle and method of construction can be used for both voltmeters and ammeters, by simply making the coil of the proper resistance and number of turns in each case.

A. C. ammeter coils usually consist of a very few turns of large wire, as they are connected in series with the load or to the secondary of a current transformer. Ammeters designed for use with shunts or current transformers, however, usually have coils of smaller wire and a greater number of turns.

Voltmeter coils are wound with a great number of turns of very fine wire, in order to obtain high enough resistance so they can be connected directly across the line.

Separate resistance coils are sometimes connected

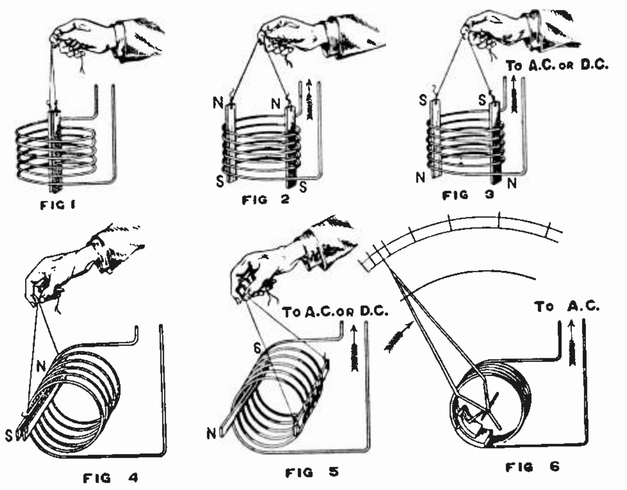

Fig. 44. The above views illustrate the principle of the moving-iron type meter. Note how the iron bars repel each other when they are magnetized with like poles, by the flux of current through the coils.

in series with the coils of voltmeters to provide sufficient resistance to limit the current through them to a very small amount. The current required to operate a voltmeter usually does not exceed a very few milli-amperes.

Fig. 45 shows a meter of the moving vane type. The iron vanes are made in several different shapes, but always operate on the same principle of the repulsion between like poles.

Some meters of this type depend upon the weight of the moving iron vane and a small adjustable counter-weight to react against the magnetic force as the pointer is moved across the scale. Other meters use a small coil spring to oppose the pointer movement.

This type of meter can be used on D. C. circuits also, but may not be as accurate, because of the tendency of the iron vanes to hold a little residual magnetism from the constant direct current flux which is applied to them.

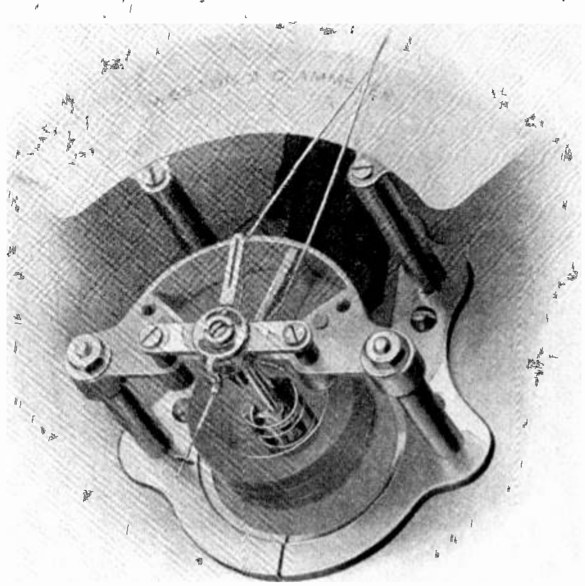

Fig. 45. This photo shows the construction and important parts of an iron-vane meter. Note the position and shape of the iron vanes within the coil and also note the damping vane and chamber above the coil.

62. DAMPING OF METERS

The damping chamber can be seen directly behind the lower part of the pointer in Fig. 45. The damping vane, made of very light-weight material and attached to the pointer, moves in this air chamber as the pointer moves. This vane doesn't touch the sides of the chamber but fits closely enough so that it compresses the air on one side or the other as it moves in either direction. This prevents oscillation of the pointer with varying loads and permits more accurate readings to be obtained.

For damping the pointer movement some instruments use a small aluminum disk which is attached to the pointer and moves between the poles of a permanent magnet. This operates similarly to the damping disk and magnet explained for D. C. watt-hour meters, the retarding effect being produced by the eddy currents induced in the disk.

Fig. 46 shows the movable assembly of the moving-iron type of instrument, on which can be seen the damping vane, mounted directly beneath the pointer, and also the movable iron vane at the lower end of the shaft, and the small coil spring which controls the pointer movement across the scale.

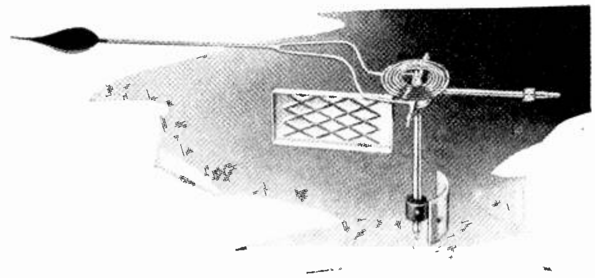

Fig. 46. Moving element of an iron-vane type meter. This view shows the shaft, iron vane, damping vane, pointer, and spring.

63. THOMPSON INCLINED COIL INSTRUMENTS

The Thompson inclined coil and moving vane type of construction is quite extensively used in some makes of A. C. voltmeters and ammeters. This type of meter uses a coil inclined at an angle of about 45 degrees with the back of the instrument, as shown in Fig. 47. This coil supplies the flux to operate a small moving vane of soft iron, which is also mounted at an angle on the shaft of the meter so that it is free to move and operate the pointer which is attached to the same shaft.

When the meter is idle and has no current flowing through the coil, the small coil spring at "C" holds the pointer at zero on the scale. When the shaft is in this position, the movable iron vane is held at an angle to the axis of the coil or to the normal path of the flux set up by the coil when it is energized.

When the coil is energized and sets up flux through its center, as shown by the arrows, the iron vane tends to move into a position where its length will be parallel to this flux. This causes the pointer to move across the scale until the magnetic force exerted is balanced by the counter-force of the spring.

This type of construction is used both for voltmeters and ammeters, by winding the coils with the proper number of turns, as previously explained.

64. DYNAMOMETER TYPE INSTRUMENTS

Dynamometer type instruments are used for voltmeters, ammeters, and wattmeters. Meters of this type have two coils, one of which is stationary and the other which is movable and attached to the shaft and pointer. The torque which moves the pointer is produced by the reaction between the fields of the two coils when current is passed through both of them.

There is no iron used in the two elements of this meter; the moving coil being light in weight

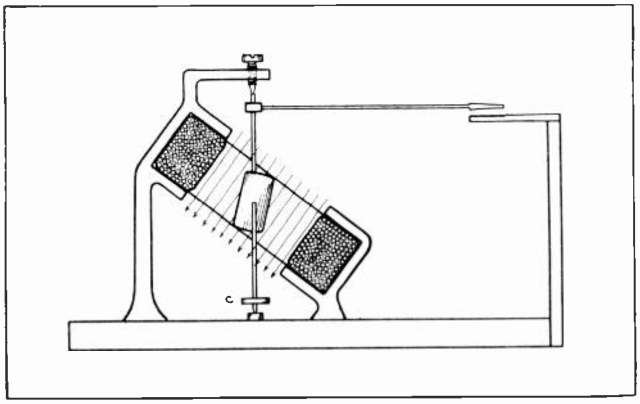

Fig. 47. The above diagram shows the construction and principle of the Thompson inclined-coil meter.

and delicate in construction, but rigid enough to exert the proper torque on the shaft.

In some meters of this type, the movable coil is mounted within two stationary coils, as shown in Fig. 48; while in other types it is mounted near to the side of one large coil, as shown in Fig. 49. In either case, the movement of the smaller coil is caused by the reaction between its flux and the flux of the stationary coil or coils.

When both the stationary and movable coils are excited or energized, the lines of force through their centers tend to line up or join together in one common path. When the pointer is at zero, the movable coil rests in a position so that its axis and the direction of its flux will be at an angle to that of the stationary coils. So, when the current is applied the reaction of the two fields will cause the movable coil to force the pointer across the scale against the opposing force of the delicate coil springs, which can be seen in both Figs. 48 and 49.

These coil springs are usually made of phosphor-bronze alloy, and in some cases they carry the current to the movable coil.

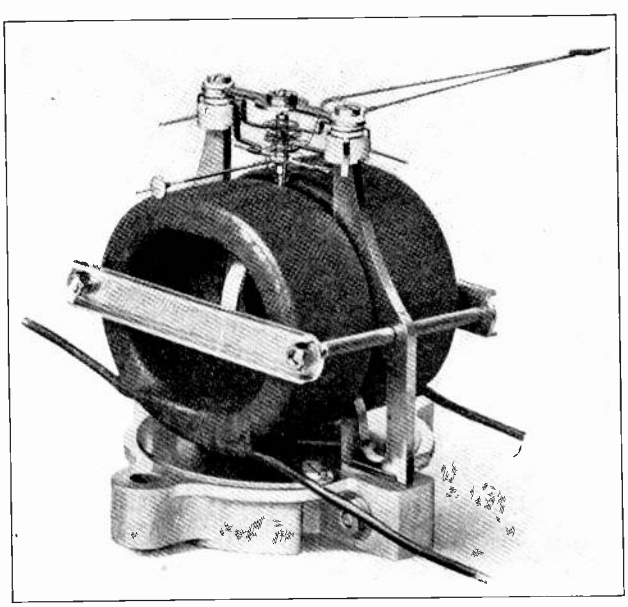

Fig. 48. This view shows the coils of an electro-dynamometer type meter.

Voltmeters of the electro-dynamometer type usually have the two coils connected in series with each other and also in series with a resistor, and then connected across the line.

Ammeters of this same type may have the two coils connected in series and then across a current transformer which carries the main load current. In some cases the stationary coil of an ammeter may carry the full load current, while the movable coil is connected to a current transformer so that it carries only a small fraction of the current.

The movable coil is not designed to carry much current in any case, because it must be light in weight and delicate in construction to obtain the proper accuracy in the operation of the meter.

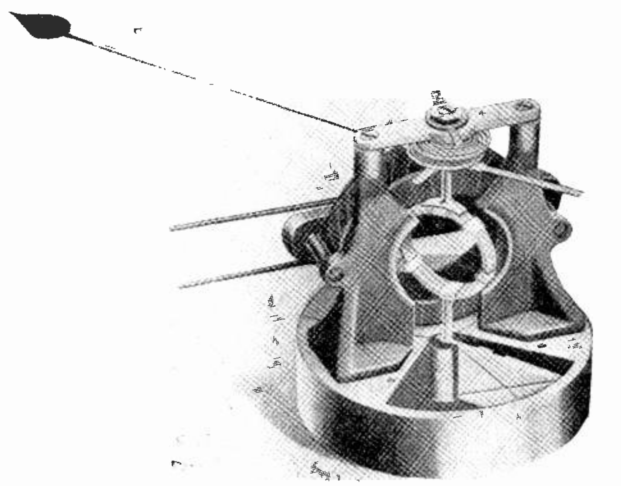

Fig. 49. Another dynamometer type meter with slightly different arrangement of the coils. Note the damping vane attached to the bottom end of the shaft so that it rotates in the damping chamber under the meter element.

65. A. C. WATTMETERS

Wattmeters using the electro-dynamometer principle have elements very similar to those shown in Fig. 48. The stationary coils are used for the current element and may be connected in series with the load or across a current transformer. The movable coil is the potential coil and is connected in series with a resistance, and then across the line.

Resistances used in connection with the coils of A. C. meters are generally of the non-inductive type, so they will not affect the reading of the meter by introducing inductive reactance in the circuit.

While shunts are used in some cases with certain types of A. C. meters, instrument transformers are also commonly used to reduce the amount of current and voltage applied to the coils of the meters. This eliminates the necessity for current coils with very heavy windings and the necessity of winding potential coils with a great number of turns to obtain high resistance to permit them to be connected across high-voltage lines. It also reduces insulation difficulties, and hazards in testing high voltage circuits.

As the current coils in the wattmeter will always carry a current proportional to the amount of load, and the potential coil will carry a current proportional to the voltage applied to its terminals, the torque set up by the magnetic fields of these two coils will be proportional to the power in watts in the circuit. The scale can therefore be graduated and marked to read directly the watts or kw. of the circuit to which the meter is connected.

Since the torque acting on the movable element is proportional to the instantaneous current and voltage, the meter will register the true power of the circuit, regardless of the power factor.

Fig. 53 shows a sketch which further illustrates the principle of the dynamometer-type wattmeter. You will note that stationary current coils which are connected in series with the line, set up a flux which tends to repel the flux of the movable coil and will cause it to move the pointer across the scale to the right.

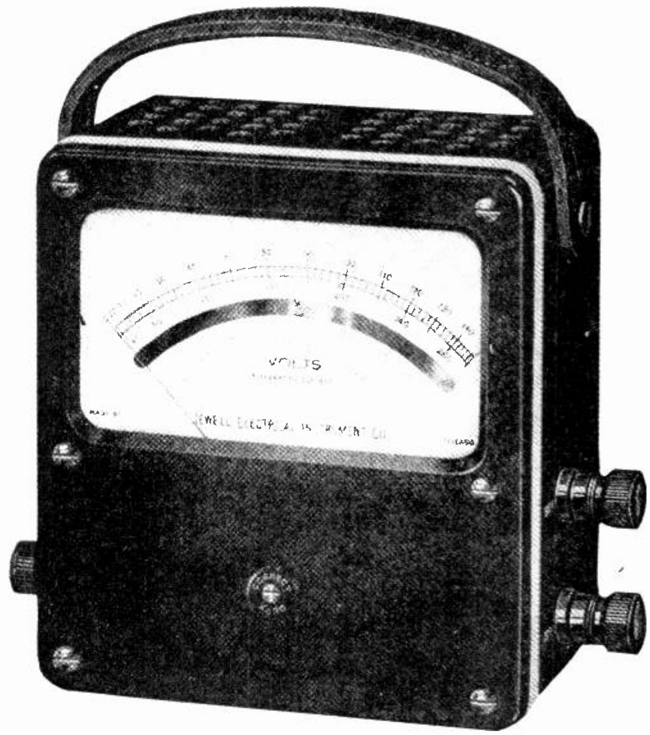

Fig. 50. A convenient style of portable voltmeter used for testing circuits and electrical machinery. (Photo courtesy Jewell Instrument Company.)

Electro-dynamometer type meters are somewhat more delicate and less simple in construction than the moving iron types, but the former are more accurate and therefore generally preferred where exact measurements are desired.

The scale over which the pointer of this instrument moves is not graduated with spaces of even width, because of the fact that the opposing force is a spiral or helical spring and, therefore, becomes greater as the pointer moves farther from zero.

66. INDUCTION TYPE INSTRUMENTS

Induction type A. C. meters operate on a principle similar to that of an induction motor, using the magnetic flux of stationary coils to induce currents in a rotating element in the form of a metal cylinder or drum, or in some cases a metal disk.

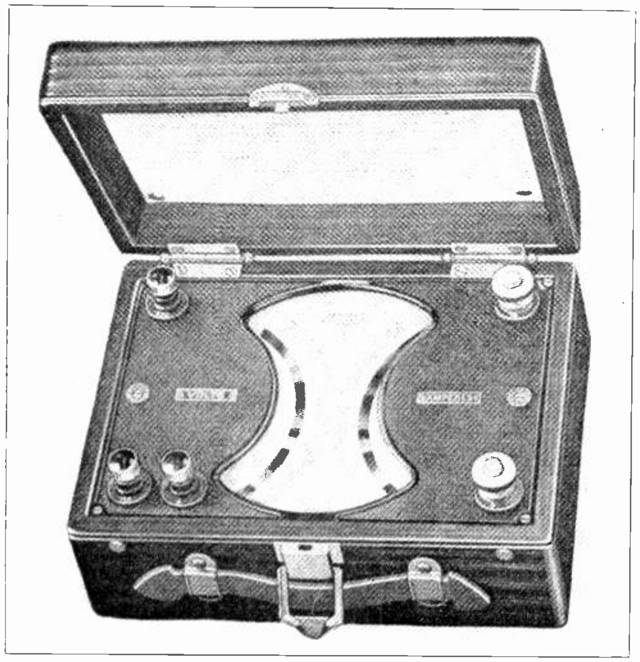

Fig. 51. This portable meter has two elements and two scales, and can be used to measure either volts or amperes. The voltmeter element has an extra terminal to provide increased voltage range of this instrument. (Photo courtesy Jewell Instrument Company.)

Fig. 57 shows a sketch of an induction meter of this type which can be used either as a voltmeter or an ammeter, according to the manner in which the coils are wound and connected.

A set of primary coils and also a set of secondary coils are wound on the upper part of the iron core. The primary coil, being connected to the line, sets up alternating magnetic flux which magnetizes the core and also induces in the secondary coils a current which is out of phase with that in the primary.

Fig. 52. Switchboard type A. C. voltmeter. Note the tapering graduation at the left end of the scale.

These secondary coils are connected in series with a third set of coils wound in slots at the lower end of the core near the movable drum. The different phase relations between the currents of these coils tend to set up a flux which is out of phase with that established in the core by the primary coil, thereby producing a sort of revolving field which induces eddy currents in the drum. The reaction between the flux of these eddy currents and the flux set up by the coils then causes the drum to tend to rotate by the same principle as used in A. C. induction motors.

The pointer is attached to this drum, so that, when the drum is rotated, the pointer is moved across the scale against the action of the coil springs.

When an instrument of this type is used for an ammeter, the primary coil is wound with a few turns of heavy wire and is connected in series with the line, or it can be wound with small wire and connected in parallel with a shunt or to the terminals of a current transformer.

When used as a voltmeter, the primary coil is wound with more turns of fine wire and is connected in series with a resistance and then across the line.

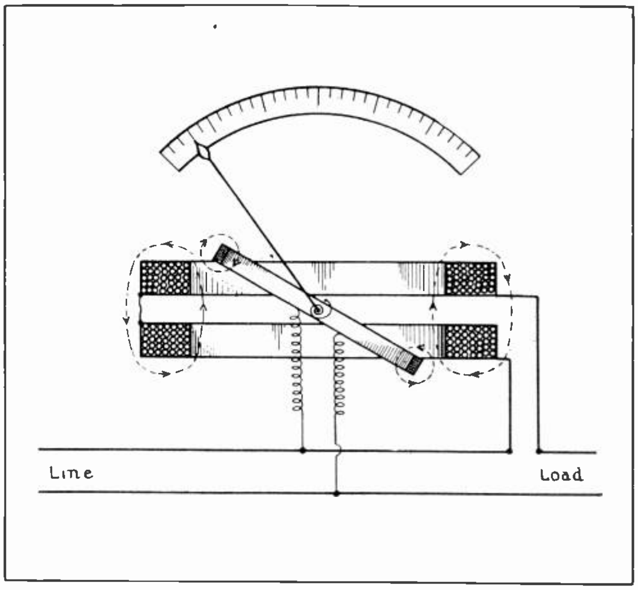

Fig. 53. This diagram illustrates the construction and principles of the dynamometer type instrument. Note the action between the flux of the moving and stationary coils.

67. INDUCTION TYPE WATTMETERS

This same induction principle can be applied to wattmeters, as shown in Fig. 58.

In this case, the potential element consists of the primary coils "P" which are connected in series with a reactance coil "B", and then across the line. The secondary coils "S" have current induced in them by the flux of the primary, and are connected in a closed circuit with a variable resistance "R".

In this manner, the amount of induced current which flows in the secondary coils may be varied by adjusting the resistance, so that the reaction between their flux and that of the primary coils

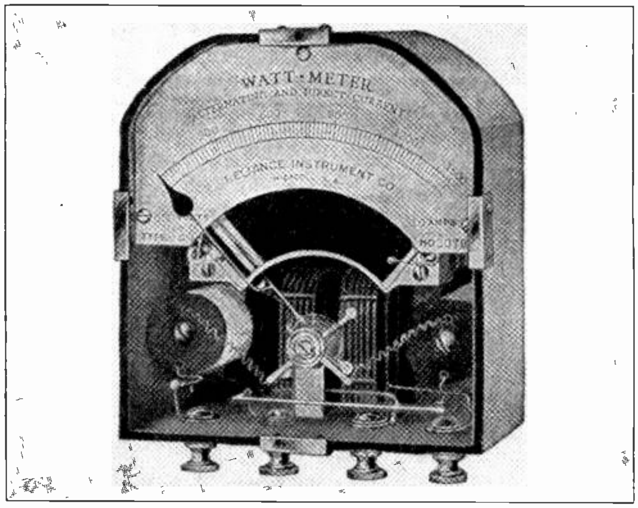

Fig. 54. This view shows the interior construction of a dynamometer type wattmeter. The current coils of the meter, the resistance coils, and damping vane in its chamber can all be plainly seen. (Photo courtesy Reliance Instrument Company.)

will produce the proper phase relation between the flux set up in the core and the flux of the current coils "C", which are wound in slots near the movable drum.

This current element is connected in series with the line, or to the proper shunt or instrument transformer.

When both sets of coils are excited, a revolving field is set up, which induces eddy currents in the movable drum, similarly to the operation of the induction voltmeter in Fig. 57.

In this case the strength of the combined flux set up by the potential and current coils will be proportional to the product of the voltage and current of the line. So, with the proper graduation of the scale, this meter can be made to record directly in watts the power of the circuit to which the meter is attached.

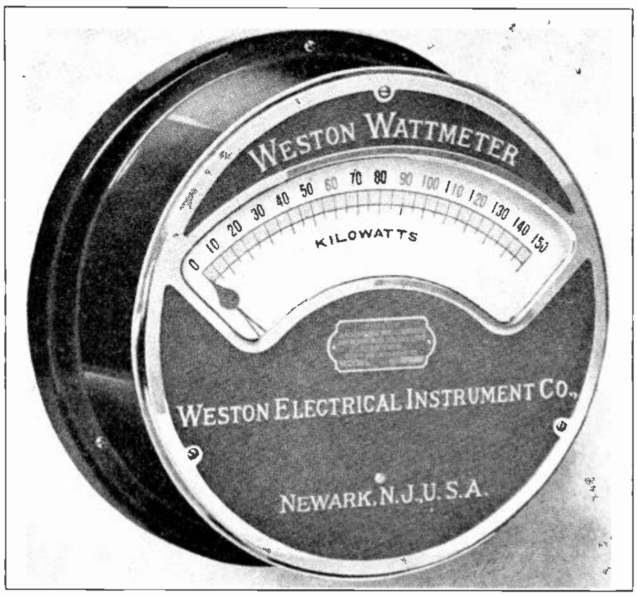

Fig. 55. Switchboard type wattmeter which has its scale calibrated to indicate the load in kilowatts. (Photo courtesy Weston Electrical Instrument Co.)

68. SHADED POLE INDUCTION METERS

Another type of induction meter which uses the **induction disk,** or shaded pole principle, is illustrated in Fig. 60.

This type of instrument has the torque produced on a moving disk, by inducing eddy currents in the disk by means of the large exciting-coil, and small shading coils, on the soft iron core.

When alternating current is passed through the large coil it sets up an alternating flux in the iron core and induces eddy currents in the edge of the disk which is between the poles of the core. The flux also induces secondary currents in the small shading coils, which are built into slots in one side of the pole faces and are short-circuited upon themselves to make closed circuits.

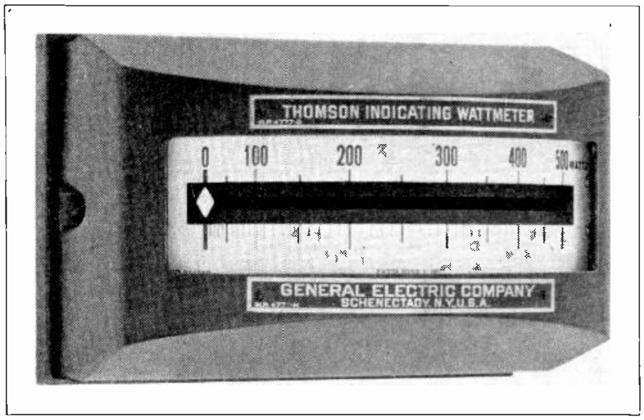

Fig. 56. Another type of switchboard meter known as the "horizontal-edgewise" type. Meters of this type are very commonly used in power plants. (Photo courtesy G. E. Company.)

The induced currents in these shading coils are out of phase with the current in the large coil, and therefore they set up flux which is out of phase with the main core flux. This causes a sort of shifting or sliding flux across the pole faces, which reacts with the flux of the eddy currents in the disk and causes the disk to tend to rotate.

The disk can rotate only part of a revolution, as its movement is opposed by a spring on the shaft. The rotating movement of the disk moves the pointer across a scale as in any other meter.

The movement of the disk and pointer is damped by the drag magnet on the right, which induces eddy currents in the disk when it moves and thereby tends to slow its movement and prevent jumping or oscillation of the pointer.

The sides of the moving disk or ring are often cut in a slightly varying or tapering width, to obtain greater torque as the pointer moves farther against the force of the spring. This allows uniform graduation of the scale.

When instruments of this type are used for ammeters, the main coil is connected in parallel with a special alloy shunt, the resistance of which changes with temperature and load changes, to compensate for heat and increased resistance in the coil or disk.

When used as a voltmeter, the coil of the instrument is connected in series with a reactance coil to compensate for changes in frequency, and also in parallel with a shunt to compensate for temperature and resistance changes.

This same principle of induction is applied to A. C. induction watthour meters, frequency meters, and various types of A. C. relays; so it is well worth thorough study to obtain a good understanding of the manner in which it produces the torque in the disk.

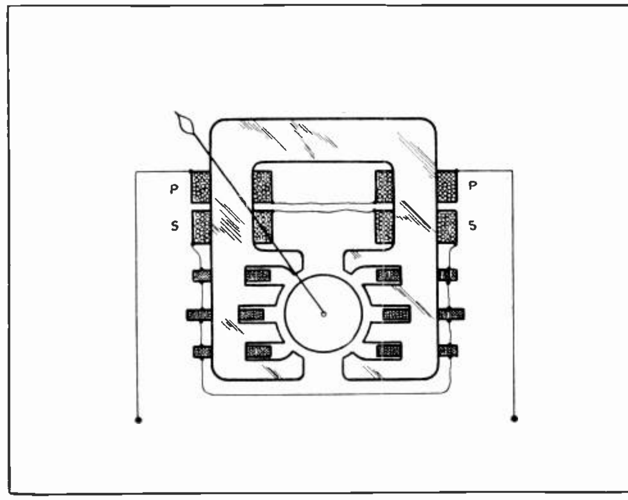

Fig. 57. This diagram shows the core and coils of an induction type meter. Study the principles of this meter thoroughly with the accompanying explanations.

69. HOT-WIRE INSTRUMENTS

Hot-wire instruments are those which obtain the movement of their pointers by the expansion of a wire when it is heated by the current flowing through it.

This principle is illustrated by the diagram in Fig. 61. When the terminals "A" and "B" are connected to a line and current is passed through the wire "W", it becomes heated by the current and expands.

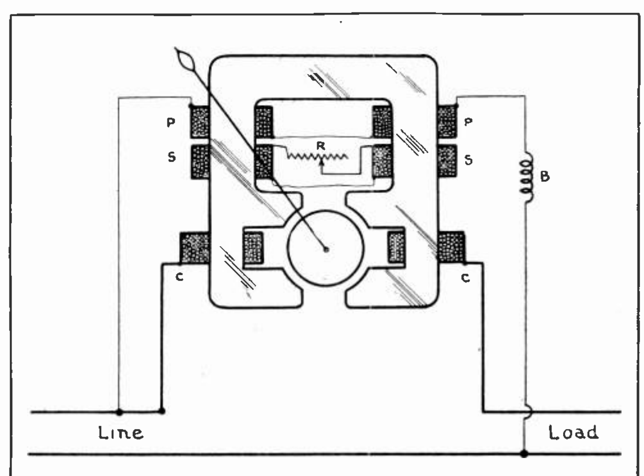

Fig. 58. Core and coils of an induction type wattmeter. Note how the current and potential coils are connected to the line.

This expansion causes it to loosen and sag, and allows wire "X" to become slack. Wire "Y" is attached to wire "X" and is wrapped around a pulley on the shaft to which the pointer is attached. The other end of this wire is attached to a spring which is fastened to the meter case. This spring maintains a continual pull on wire "Y"; so that, as soon as wire "X" becomes slack, wire "Y" is drawn around the pulley and causes it to rotate and move the pointer across the scale.

When the current decreases or stops flowing through wire "W", this wire cools and contracts back to its tight condition and draws wires "X" and "Y" back against the action of the spring; thus returning the pointer to zero.

When instruments of this type are used as ammeters, the wire "W" is connected in series with the line or in parallel with a shunt which is in series with the line. When the device is used as a voltmeter, the wire "W" is connected in series with a resistance and then across the line.

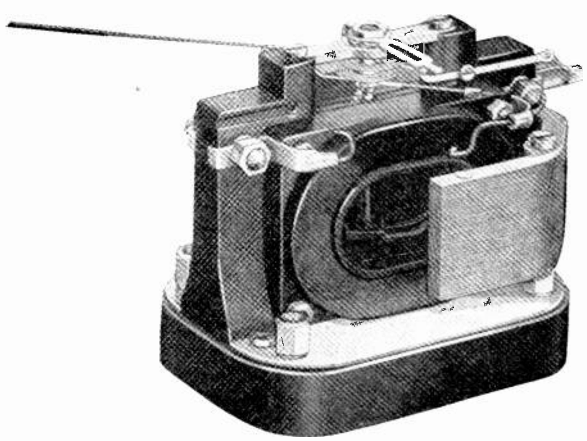

Fig. 59. This photo shows a meter element with part of the magnetic shield in place around it. These shields are made of soft-iron laminations and prevent magnetic flux from other machines or circuits from interfering with the accuracy of the meter. One-half of the shield is shown removed in this view.

Hot-wire instruments are made in a number of different forms, and with various arrangements of their wires and parts; but all of them operate on the same general principle. Fig. 62 shows the working parts of a hot-wire meter of slightly different construction from that shown in Fig. 61.

Meters of this type can be used on either D. C. or A. C. circuits; but they are particularly adaptable to high frequency A. C. circuits, such as in radio stations, X-ray work, and laboratories where very high frequencies are used. Having no coils in their construction, hot-wire meters are non-inductive and therefore offer less impedance to high frequency currents and operate more accurately on varying frequencies.

70. ELECTRO-STATIC VOLTMETERS

Electro-static voltmeters are often used for measuring very high voltages. These meters operate on the principle of the attraction between bodies with unlike charges of static or high-voltage elec-

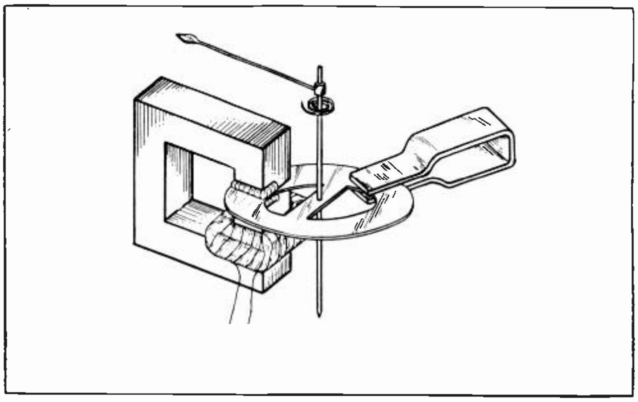

Fig. 60. Diagram illustrating the principles and construction of a disk type induction meter. The torque on the disk is produced by the action of the flux from the shaded pole.

tricity. Fig. 63 shows an electro-static voltmeter, with the case opened to show all the working parts clearly.

This instrument consists of a set of stationary metal vanes, and a pair of movable vanes of light weight metal. In normal or zero position, the movable vanes hang free of the stationary vanes due to gravity action on a counter-weight attached to the shaft.

When the wires of a high-voltage line are connected to this instrument, one wire to the stationary vanes and one to the movable vanes, charges of opposite polarity will be set up on the vanes. This causes them to attract each other and the movable vanes will be drawn nearer to the stationary ones, or in between them. This moves the pointer across the scale a distance proportional to the voltage applied.

Electro-static voltmeters can be obtained to measure voltages as high as 50,000 volts, or even more. They can also be made to measure quite low voltages, by using a number of vanes, closely

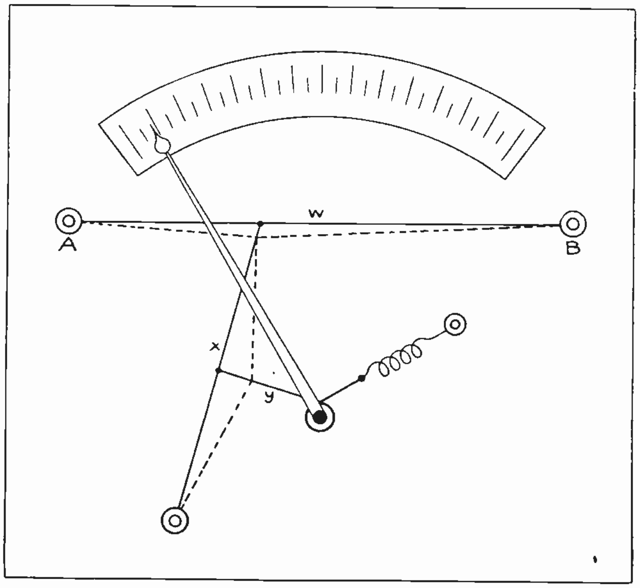

Fig. 61. This sketch shows the operation of a hot-wire meter, in which the movement of the pointer is obtained by the expansion of a wire when heated by passing current through it.

spaced. These instruments will work on either D. C. or A. C. circuits, because it makes no difference if the polarities reverse, as long as the movable and stationary vanes are always of opposite polarity at any instant.

71. A. C. WATTHOUR METERS

A. C. watthour meters are quite similar in many ways to those for D. C., which were explained in the section on D. C. meters. They consist of current coils and potential coils which set up flux and turning effort on the rotating element. The rotating element drives a chain of gears which operate the pointers on a row of four dials, and total up the power used in kilowatt-hours.

Some A. C. watthour meters are of the electro-dynamometer type. They have the potential coil wound on the moving armature and are equipped with commutator and brushes similar to those of D. C. watthour meters. The more common type of A. C. meter uses the induction disk principle, as meters of this type are much simpler and more rugged, have fewer wearing parts, and therefore require less care than the other types.

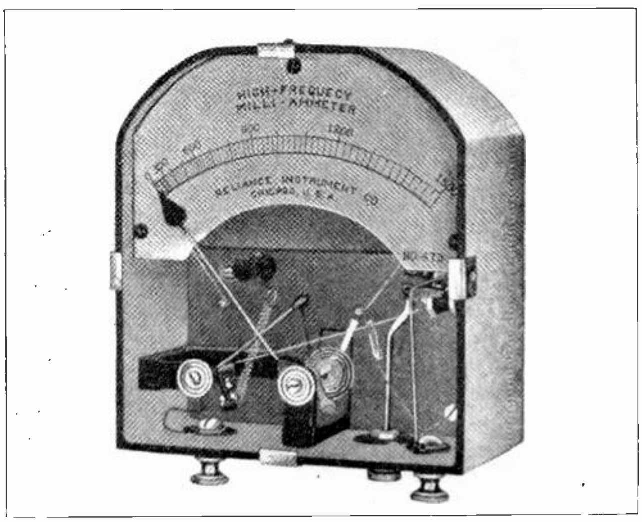

Fig. 62. This view shows the inside parts of a hot-wire meter of slightly different construction than the one illustrated in Fig. 61.

In the induction type watthour meter, both sets of coils are stationary and the rotating element is simply a light-weight aluminum disk mounted on a vertical shaft. There are no commutators or brushes to produce friction or get out of order. Fig. 64 is a photo of a modern A. C. induction watthour meter, and it shows clearly the principal parts of such a meter, with the exception of the gears, dials, and the damping magnets, which are on the other side of the meter.

The two coils of heavy wire on the lower part of the core are the current coils, and the large coil above is the potential coil. Between these coils the rotating disk can be seen.

Fig. 65 shows a diagram of the core, coils, disk, and one damping magnet of a meter of this type, and further illustrates its operating principle.

The potential coil "P" is wound with a great number of turns of very fine wire, and on the upper leg of the soft, laminated-iron core; and the current coils "C" and "C" are wound with very few turns of heavy wire, on the two lower core legs.

The large number of turns in the potential coil make this winding highly inductive, and cause the current which flows through it to be nearly 90 degrees lagging, or out of phase with that in the current coils. As the current coils consist of only a very few turns, their circuit has very little inductance, and the current through them will be nearly in phase with the line voltage.

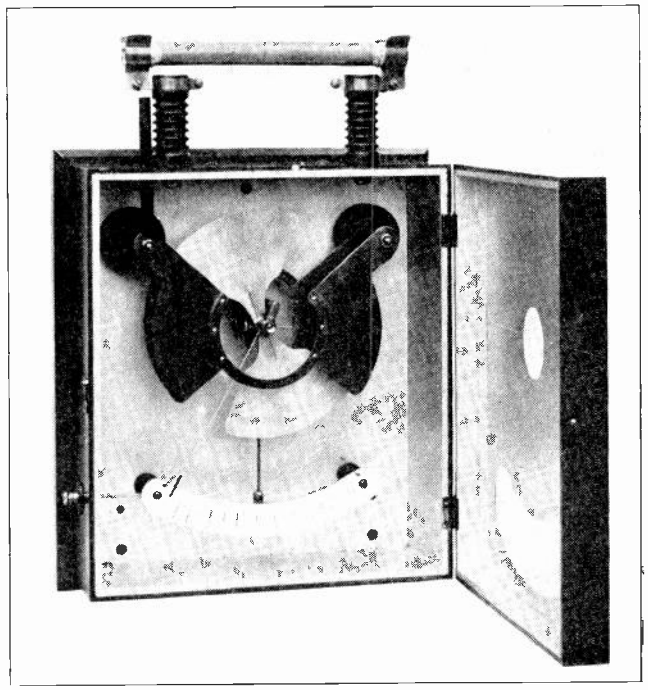

Fig. 63. This photo shows an electro-static voltmeter for measuring the potential of high voltage circuits. The pointer movement is obtained by the attraction between the moving and stationary metal vanes when they are charged with opposite polarity.

The potential coil is connected across the line or across the terminals of a potential transformer. The current coils are connected in series with the line on small power and lighting circuits; or to the secondary of a current transformer on heavy power circuits.

The reversing flux of the current coils alternately leaves one of these poles and enters the other; while the flux of the voltage coil leaves its pole and splits or divides between the two poles at its sides and the two poles of the current coils under the disk.

These two different fluxes which are set up by the out-of-phase currents in the potential and current coils, create a shifting or rotating field effect, which induces eddy currents in the disk; and the reaction between the flux of these eddy currents and the main flux causes the torque and rotation of the disk. This is called the motor element.

One of the damping or "drag" magnets is shown at "D" in Fig. 65. There are two of these magnets, located one on each side of the disk; and when

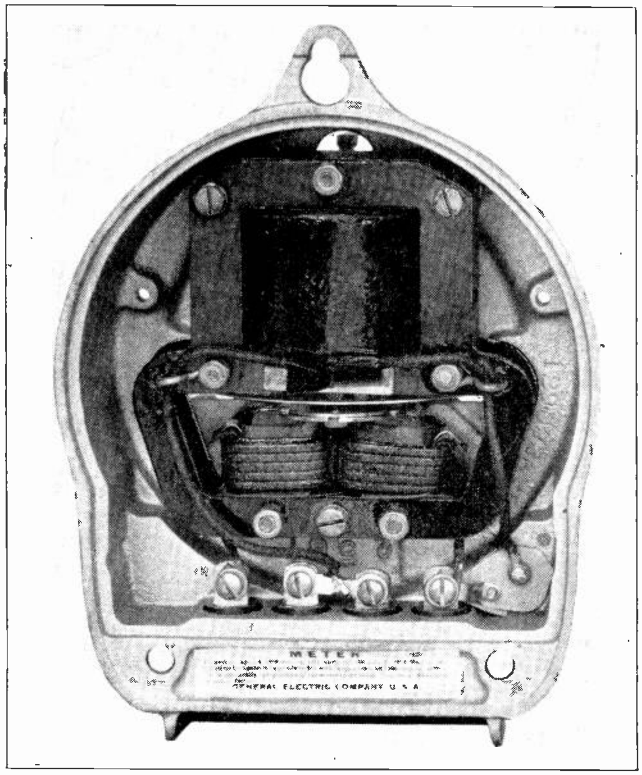

Fig. 64. Interior view of a modern watthour meter, showing the current and potential coils, and the induction disk.

the edge of the disk revolves between the magnet poles, their flux induces in the disk eddy currents which tend to retard its motion. This retarding or damping force will always be proportional to the speed of the disk.

As the current and flux of the potential coil are proportional to the line voltage, and the current and flux of the current coils are proportional to the load current, the torque exerted on the disk by these fluxes will always be proportional to the product of the volts and amperes. This is also proportional to the load in watts on the line.

This force acting against the retarding effect of the damping magnets will cause the meter speed to be proportional to the power used at any time.

The upper end of the shaft on which the disk is mounted is fitted with a worm which drives the first gear of a chain of several gears, which in turn operate the pointers, exactly as described for D. C. watthour meters in Article 102, Section Two, of Direct Current.

A. C. watthour meters are also read in exactly the same manner as explained in Article 103 of Section Two on Direct Current.

72. CREEPING

Sometimes the disk of an A. C. watthour meter will continue to revolve very slowly when the load is all disconnected from its circuit. This is known as **creeping**; and it may be caused by vibration, too high line-voltage, wrong adjustment of the friction compensating device, wrong connection of the potential coil, a short circuit in the current coil; or by a high-resistance ground or leakage on the line.

The potential coil of a watthour meter is connected directly across the line; so, as long as there is voltage on the line, there will always be a very small amount of current flowing in this coil whether there is any load on the line or not.

If the meter is over-compensated for friction by the light load adjustment, this may set up enough torque to rotate the disk slowly. Vibration of the meter reduces the friction on its bearings and may be the cause of starting the creeping.

If the line voltage rises above normal, it will increase the amount of current flowing in the potential coil and thereby increase the torque set up by the light-load, friction-compensating device.

The potential coil should be connected across the line between the current coils and the service, as shown in Fig. 65; because, if it is connected on the load side of the current coils, the small current which is always flowing through the potential coils will also flow through the current coils, and may set up enough flux and torque to cause the meter to creep.

If a short-circuit occurs in the current coils, making a closed circuit of one or more turns, the flux of the potential coil will induce a current in these shorted turns. The flux of this secondary current, working on the disk with that of the potential coil, will cause the meter to creep.

High-resistance grounds or leaks on the line may cause enough current leakage to operate the meter slowly, and yet not enough current to blow a fuse.

Some watthour meters have two small holes drilled on opposite sides of the disk to prevent creeping. The nature of the eddy currents set up around these holes will tend to stop the disk when the holes come between the poles of the magnets.

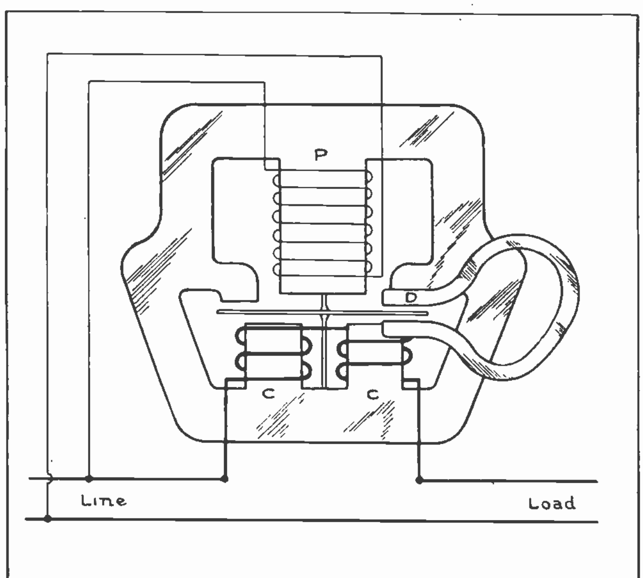

Fig. 65. This diagram illustrates the construction and principles of an induction watthour meter. Note the manner in which the current and potential coils are connected to the line.

73. A. C. WATTHOUR METER ADJUSTMENTS

The light-load adjustment, or friction compensation, on some watthour meters consists of a small coil placed near the current or potential coil and short-circuited so that it will have current induced in it by the flux of the main coil. The current and flux of this auxiliary coil are out of phase with those of the main coils, so they set up a small amount of "split-phase" or shifting flux, which adds just enough to the torque of the disk to compensate for friction at light loads.

In other meters, this adjustment consists of a small plate located between the disk and the poles of the current coil cores, to distort part of their flux and thereby produce a slight shifting flux and torque on the disk. These auxiliary coils or plates are usually adjustable by means of a screw, so that they can be accurately set to provide the right amount of compensation.

Fig. 66. Watthour test meter or rotating standard, used for calibrating watthour meters.

A. C. watthour meters often have another adjustment to compensate for inductive load and lagging current on the line.

On some of the latest type meters this adjustment consists of a copper punching mounted under the meter disk and directly under the pole of the potential coil.

The secondary current induced in this copper plate, or ring, sets up flux of a proper phase relation with the main field to compensate for lagging load currents.

By moving this plate back and forth by means of an adjusting screw, the meter can be adjusted properly for various inductive loads.

The **full-load adjustment** for calibrating watthour meters is made by shifting the damping magnets in or out at the edge of the disk.

If the meter runs too fast, the poles of the permanent magnets are moved farther out on the disk, to produce a greater retarding effect. If the meter runs too slowly, the damping magnets are moved farther in.

On later type meters, the damping magnets are mounted in a brass clamp which is adjustable by means of a screw.

74. TEST METERS AND POLYPHASE WATTHOUR METERS

Fig. 66 shows a portable test meter or **rotating standard,** used for calibrating and adjusting watthour meters, in the manner explained in the section on D. C. meters. This test instrument is connected to the same circuit or load as the meter under test, and the number of revolutions of its pointer are compared with the revolutions of the meter disk. By this comparison, and careful consideration of the watthour constant on the disk of the meter, we can determine whether the meter under test is operating accurately, or is running too fast or too slowly.

Polyphase watthour meters are used for measuring the power in kw. hours in a three-phase circuit. These meters have two or three separate elements for measuring the power either by the "two meter" or "three meter" method.

Fig. 67 shows a polyphase induction watthour meter for use on a three-phase, four-wire circuit.

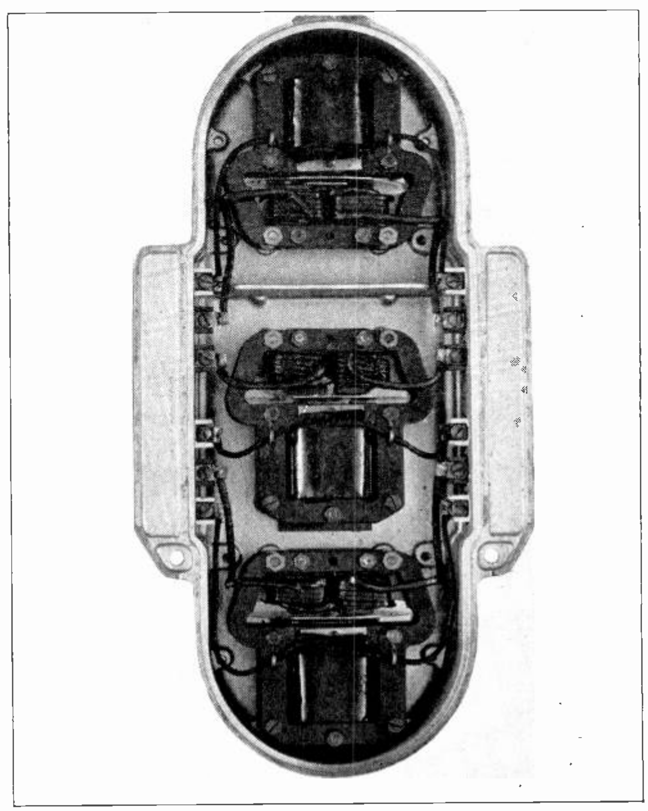

Fig. 67. This photo shows a three-phase watthour meter with three separate meter elements, one of which is connected to each phase.

75. DEMAND INDICATORS

In the section on D. C. meters one type of maximum demand indicator was explained. This type, you will recall, uses the heating effect of the load current to expand the air in a glass tube, and force a liquid over into an index tube to indicate the maximum demand on the system. This same type of demand indicator can also be used on alternating current systems.

In addition to this thermo-type of demand indicator, other A. C. maximum demand indicators are used which are operated either by electro-magnets or the induction disk principle.

One of these is simply a wattmeter element which moves a pointer over a scale a certain distance proportional to the maximum load, and leaves the pointer locked in this position until a higher load advances it farther, or until it is reset by the meter reader. This type is known as an indicating demand meter.

Another type has a marker operated by a magnet so it makes a mark on a moving paper tape each time the watthour meter makes a certain number of revolutions. These are called recording demand indicators.

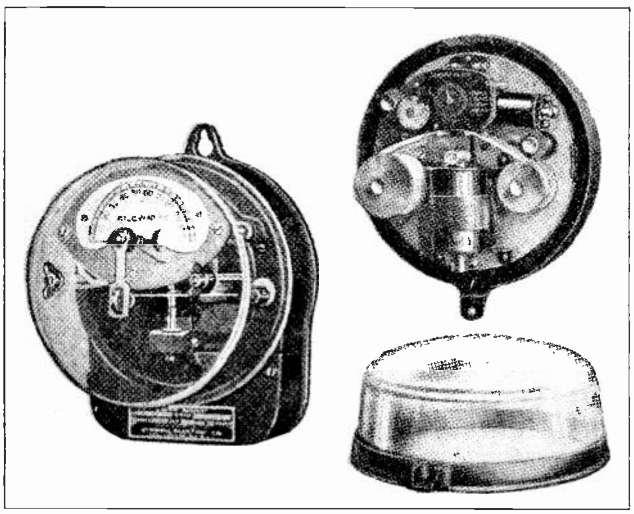

Fig. 68. Two types of maximum demand indicators. The one on the left is of the indicating type, and the one on the right is a recording type meter.

These indicators are used in connection with a watthour meter which is equipped with a contact-making device, so that it closes the circuit to the control magnet coils of the demand indicator every time the watthour meter makes a certain number of revolutions.

On the indicating type of demand meter, the pointer or needle is advanced across the scale a distance proportional to the amount of maximum load during any period that the instrument is energized.

On recording type demand indicators the speed of the tape is constant, so the number of marks for any given time period will vary in frequency and spacing according to the speed of the watthour meter during that period.

These marks, therefore, provide an indication of the maximum amount of power during any period.

Spring wound clocks or electric clocks are often used with demand indicators to control the time element or tape.

Some of the spring type clocks used with these meters, will run from 8 to 40 days with one winding.

Fig. 68 shows an indicating type of maximum demand meter on the left, and one of the recording type at the right. The cover is removed from the instrument at the right, showing the magnet coils and paper tape on which the record is printed.

Recording wattmeters using paper charts and operating on the same general principles as the recording wattmeters explained in the D. C. Meter Section, are also used in A. C. work.

76. POWER-FACTOR METERS

It has previously been mentioned in this section that power-factor meters can be used to indicate directly the power factor of any A. C. circuit. Power-factor meters are designed to register on their scale the power factor, or the cosine of the angle of lag or lead between the current and voltage of the circuit to which they are attached.

There are a number of different types of power-factor meters. One of the very common types which operates on the electro-dynamometer principle is illustrated in Fig. 69. This instrument has two movable coils, "A" and "B", mounted at right angles to each other on the shaft to which the pointer is attached. Coil "B" is connected in series with a resistance unit, "R", and coil "A" in series with an inductance "S"; then they are connected across the line of which the power factor is to be measured.

The stationary coils, "Z" and "Z-1", are connected in series with each other and then in series with one side of the line. The current through coil "B" will be approximately in phase with the line voltage; while the current through coil "A" will lag nearly 90 degrees behind the voltage, because of the inductance which is connected in series with this coil.

As the stationary coils are connected in series with the load, their current will be in phase with the load current. At unity power factor, the current through the stationary coils will be in phase with the current through the movable coils "A" and "B", and their magnetic fields will be at maximum value at the same time.

The flux of these coils tends to line up or flow through the same axis, and therefore holds coil "B" in its present position with the needle resting at 1.00, or unity power factor.

This is also often called 100 per cent. P.F.

While the power factor is unity, the current and flux of coil "A" will be approximately 90 degrees out of phase with the flux of the stationary coils; therefore, there will be just as much tendency for this coil to try to turn in one direction as in the other, so it doesn't exert any definite torque in

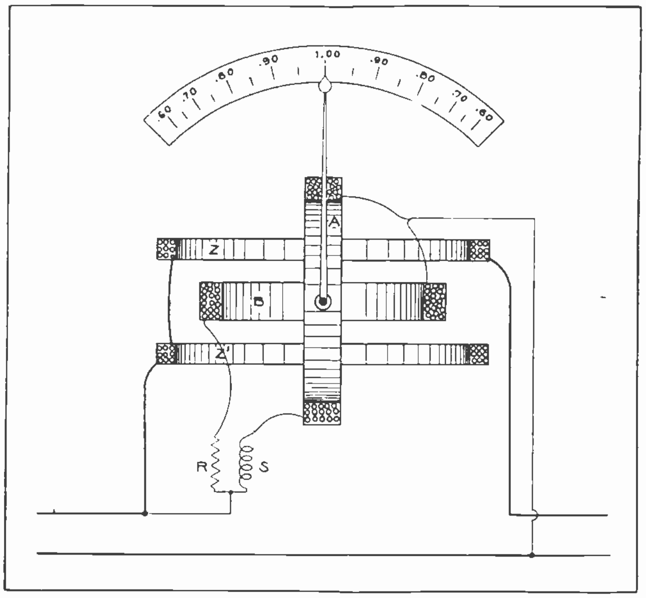

Fig. 69. This diagram shows the important parts and operating principles of a power factor meter.

either direction and allows coil "B" to hold the pointer in an upright position.

If the line current and voltage were approximately 90° out of phase, then the current in coil "A" would be in phase with the current in the stationary coils, and its flux would tend to turn coil "A" until its axis lines up with that of the stationary coils "Z" and "Z-1". It may turn either to the right or left according to whether the current lags or leads the line voltage.

During such a period, when the line current lags the voltage nearly 90°, the flux of coil "B" would be approximately 90° out of phase with the flux of the stationary coils, and it would therefore exert no appreciable torque in either direction.

If the line current and voltage were about 45° out of phase with each other, then the flux of both coils "A" and "B" would tend to line up with the flux of the stationary coils and the needle would assume a position of balance at about 71% power factor.

In this manner, any degree of lag or lead of the line current will cause the two coils to take a corresponding position, dependent upon the angle between the currents in the stationary coils and those in coils "A" and "B".

When the instrument is used as a power-factor indicator, the scale is marked to indicate the cosine of the angle of lag or lead, so that the power factor can be read directly from the scale.

The scale of this meter can also be marked to indicate in degrees the amount of lag or lead in the current, and can then be used to indicate the phase relations between the line voltage and the current.

Fig. 70 shows a switchboard-type power-factor meter. The scales of these instruments are seldom marked lower than 45 or 50 per cent, because it is very seldom that the P.F. is found to be lower than this on any system. You will note that the needle can swing either to the right or left of unity and thereby indicate whether the power factor is lagging or leading.

Meters of this type will operate satisfactorily with voltage variations as much as 25% either below or above normal.

Single-phase power-factor indicators will not give accurate readings if the frequency of the circuit varies more than 2%. For high-voltage or heavy power circuits, current and potential transformers are used with such meters to reduce the voltage and current applied to their windings.

Power plants and large industrial plants which use considerable amounts of alternating current power are usually equipped with power-factor meters, and portable instruments of this type can often be used to make very valuable tests on machines or circuits throughout various plants.

77. FREQUENCY METERS

A frequency meter is an instrument which, when connected across the line the same as voltmeters are connected, will indicate the frequency of the alternating current in that line.

There are many cases where it is necessary to know or maintain the exact frequency of certain circuits or machines, and in such cases a frequency meter is used to conveniently determine the frequency of the circuit.

Power plants supplying A. C. usually regulate the frequency very carefully so that it will stay almost exactly at 60 cycles per second, or whatever the frequency of the generators is intended to be.

There are two types of frequency meters in common use, one known as the vibrating-reed type and the other of the induction type.

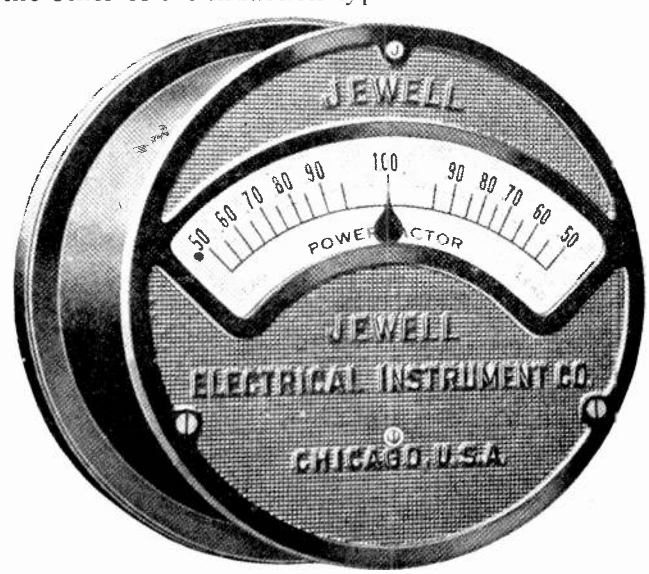

Fig. 70. Switchboard type power factor meter, such as commonly used in power plants and large industrial plants.

78. VIBRATING-REED TYPE INSTRUMENT

A vibrating-reed instrument is a very simple device, consisting principally of an electro-magnet which is excited by the alternating current, and a number of steel reeds which are like thin, flat springs. These reeds are caused to vibrate by the changing strength and reversing flux of the magnet.

Fig. 71 illustrates the principle of this type of frequency meter. The large electro-magnet is wound with a coil of fine wire which is connected in series with the resistor and across the line. When alternating current is passed through this coil, it magnetizes the core first with one polarity and then another.

The polarity is constantly reversing and varying in strength, in synchronism with the frequency of the current. This causes the ends of all the steel reeds to be slightly attracted each time the end of the magnet becomes strongly charged.

These reeds are about 1/8 of an inch wide and approximately 3 inches long, but they each have slightly different natural periods of vibration. In other words, they are somewhat like tuning forks which will vibrate more easily at certain frequencies, depending upon the weight and springiness of the elements.

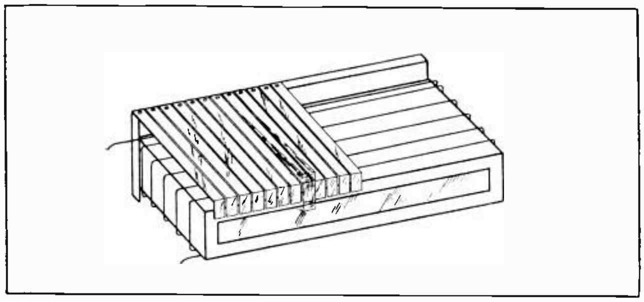

Fig. 71. Diagram of a vibrating-reed type frequency meter. Only part of the reeds are shown in this view. Note the appearance of one reed which is vibrating more than the others.

The reeds of the frequency meter can be made to vibrate at different frequencies either by making them of slightly different thicknesses or by weighting the ends very accurately with small amounts of lead. In this manner they are graduated from one end of the instrument to the other, so that the reeds on one end have a lower rate of vibration, and as they progress toward the other end each one has a slightly higher rate of vibration.

This arrangement will cause one or two of the reeds which have a natural rate of vibration closest to the frequency of the alternating current, to vibrate more than the others do when the magnet coil is energized.

The vibration of most of the reeds will be barely noticeable, because the magnetic impulses do not correspond with their natural frequencies. But the reed which has a natural vibration rate approximately the same as that of the alternating current, will vibrate up and down from 1/8 to 1/4 of an inch or more, and perhaps one reed on each side of it will vibrate a little.

The front ends of the reeds are bent downward in short hooks to make them plainly visible and, when viewing them from the front, the end of the reed which is vibrating will appear longer than the others. Then, by reading on the scale directly under this vibrating reed, the frequency can be determined.

Another meter using this same principle, but of slightly different construction, is shown in Fig. 72. This meter has the reeds attached to a bar, "B", that is mounted on a stiff spring, "S", in such a manner that the whole bar with all of the reeds can be vibrated. There is also an iron armature, "A", attached to this bar and projecting out over the reeds beneath the poles of a pair of electro-magnets, "M".

These magnets are excited by the alternating current, the same as the large magnet shown in Fig. 71, and they cause the iron armature to vibrate and rock the bar, thereby causing the reeds to vibrate also.

This vibration of the reeds will be hardly noticeable, except on those that have a natural rate of vibration the same as the speed of the bar movement and the frequency of the alternating current which excites the magnets. These several reeds will vibrate so that their ends will be plainly noticeable, as previously explained.

This type of frequency meter has an adjusting screw for varying the distance between the electromagnets and the armature "A". By changing this adjustment, the amount of vibration of the reeds can be regulated.

If the circuit to which a meter of this type is connected has a frequency of 60 cycles, the reed directly above the number 60 on the scale will be the one which vibrates the most.

This reed, however, will be moving at the rate of 120 vibrations per second, or once for each alternation of the 60 cycles.

79. INDUCTION-TYPE FREQUENCY METERS

The induction-type frequency meter is more commonly used than the vibrating-reed type. This meter operates on the induction-disk and shaded-pole principle, similar to that which was explained for induction voltmeters and ammeters.

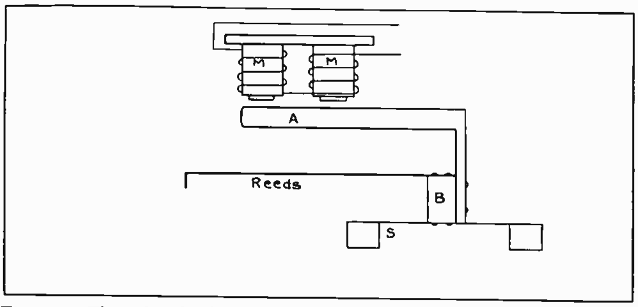

Fig. 72. This sketch shows a side-view of another type of vibrating-reed frequency meter. This instrument uses a pair of small electro-magnets to vibrate the armature to which the reeds are attached.

Fig. 73-A shows a side view of the cores, and disk of an induction-type frequency meter.

Each of the cores, "C" and "C-1", is wound with exciting coils, one of which is connected in series with a resistor "R", and the other in series with an inductance "X".

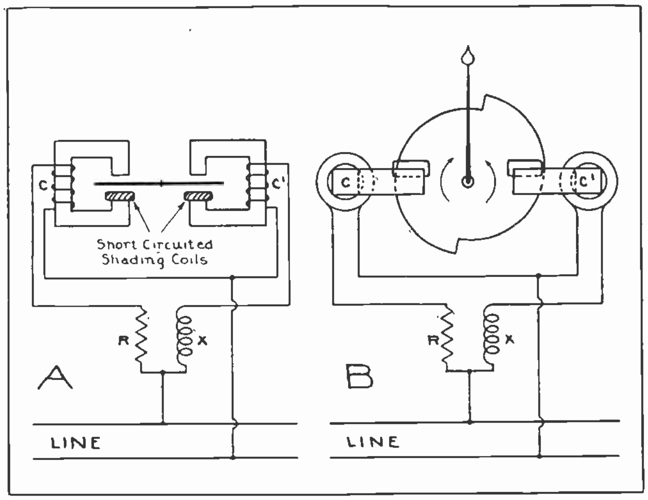

Fig. 73. "A" shows a side-view of an induction type frequency meter. This instrument uses the shaded-pole method of producing torque on the disk by induction. "B". Top view of an induction frequency meter, showing the shape and position of the disk between the poles.

These inductance coils, such as shown at "X", are sometimes called **reactors**. One end or pole of each of the magnet cores is equipped with a shading coil or small, short-circuited coils which are imbedded in one side of the pole faces.

When the coils "C" and "C-1" are excited with alternating current, the flux which is set up in the cores induces secondary currents in the short-circuited shading coils. The flux from these secondary currents in the shading coils reacts with the flux from the main coils and sets up a shifting flux across the edges of the disk.

This induces eddy currents in the disk and tends to set up torque and rotation of the disk. The position of the shading coils and the shape of the disk can be noted in Fig. 73-B.

You will also note in this view that the shading coils are placed on the same side of each magnet, so that they will both tend to exert opposing forces on the disk, each trying to revolve the disk in the opposite direction.

When the instrument is connected to a circuit of normal frequency, or 60 cycles, the current flow through each of the coils "C" and "C-1" will be balanced, and the pointer will remain in a vertical position as shown.

You will recall that the inductive reactance of any coil varies in proportion to the frequency. Therefore, if the frequency of the line increases or decreases, it will vary the amount of current which can pass through the inductance "X" and the coil "C-1".

If the frequency is increased, the inductive reactance of coil "X" will become greater and decrease the current through coil "C-1". This will weaken the torque exerted on the disk by this magnet and allow the disk to rotate a small distance to the right.

If the line frequency is decreased below normal, the inductive reactance of the coil "X" becomes less, allowing more current to flow and strengthen coil "C-1". This will cause the disk to rotate to the left a short distance.

If the disk were perfectly round it would continue to rotate; but it is so shaped that the side under the poles of coil "C" always presents the same amount of surface to the pole, while the side under the poles of coil "C-1" presents a smaller area to the pole as the disk revolves to the left. Therefore, it will turn only a short distance until the increased strength of coil "C-1" is again balanced by the decreased area of the disk under this pole.

The reverse action takes place as the disk rotates to the right, so it will always come to rest at a point corresponding to the frequency of the line to which the meter is connected. The current through coil "C" remains practically constant, because it is in series with the resistor, and the impedance of this non-inductive resistor does not vary with the changes in frequency.

Fig. 74 shows a switchboard-type frequency meter with the needle resting in the normal position, indicating 60 cycles frequency. The scale is graduated to indicate frequencies as low as 50 cycles and as high as 70 cycles per second.

Instruments of this type will operate satisfactorily on voltages either 25% below or above normal. When used on 110-volt circuits, these meters are usually connected directly across the line, the same as a voltmeter.

80. CONNECTIONS OF FREQUENCY METERS

When used on higher voltage, a potential transformer can be used to step the voltage down. In other cases a resistance box may be used in series with the meter so that it can be operated directly from lines as high as 440 volts.

Fig. 74-A shows the connections of a frequency meter of this type, with its resistance and reactance units which are enclosed in one box. There are

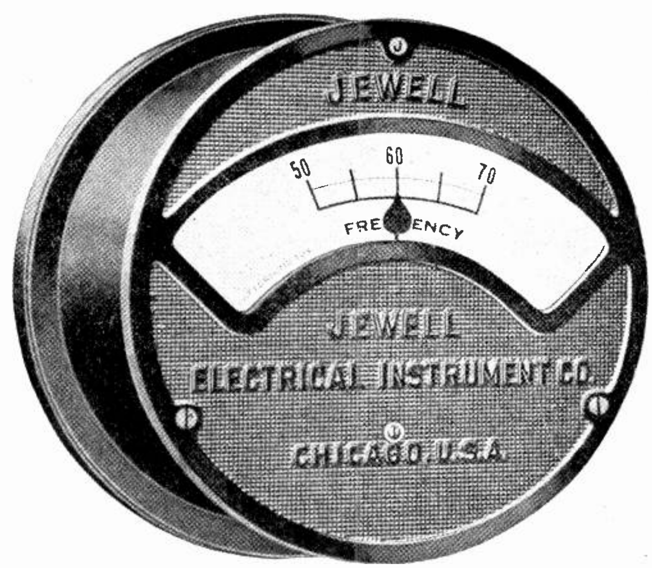

Fig. 74. This photo shows a switchboard type frequency meter, such as commonly used in power plants. The connections to instruments of this type are made to brass terminal bolts which project through the switchboard from the back of the meter.

three terminals on the meter and three on the resistance and reactance unit.

The terminal "R" of the reactance box is connected to the right-hand terminal of the meter, while the terminal "L" from the box connects to the left-hand terminal of the meter. The center terminal of the meter connects to the line wire opposite to that to which the common wire of the reactance box is connected.

Sometimes these meters fail to register properly because of no voltage or very low voltage on the circuit, or because the moving element has become stuck. If the meter reads extremely high, it may be caused by a bent disk, a short-circuit in the resistance coil, or an open circuit in the reactor coil. Testing with a voltmeter will locate either of these faults in the resistance and reactance box.

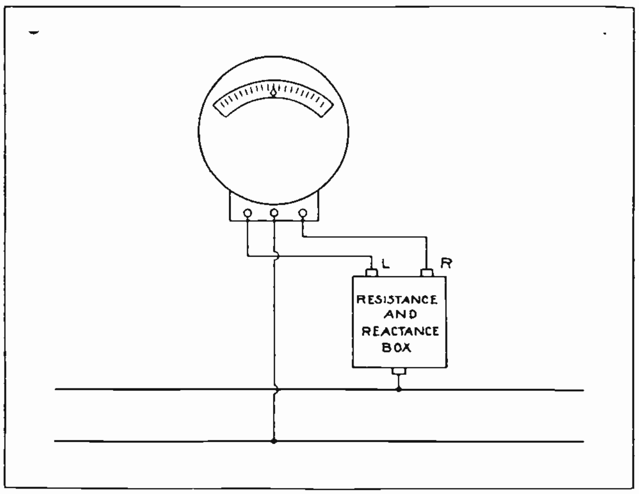

Fig. 74-A. This sketch shows the connections for a frequency meter and the resistance and reactance box which is used with the meter.

If the meter reads too low, it may be due to the moving element having become stuck or to an open circuit in the resistance unit. If the meter reads opposite to what it should, that is, if the needle indicates a lower frequency when you know the frequency is increased, or if it indicates a higher frequency when the line frequency is decreased, then the two outside terminals at the meter or at the reactance box should be reversed.

81. SYNCHROSCOPE

When paralleling A. C. generators, it is necessary to have a device to indicate when the machines are in phase or in step with each other. For this purpose an instrument called a **synchroscope** is used.

A synchroscope will indicate the phase difference between the running generator and the one which is being brought on to the bus, and will also indicate which machine is running the fastest, so that their speeds can be properly adjusted and the machines brought into perfect step or in phase with each other. This synchronizing is absolutely necessary before paralleling any A. C. generators.

The construction and operation of the ordinary synchroscope is practically the same as that of a single-phase power-factor meter.

Fig. 75 shows the construction and connections of a common type of synchroscope. The operating principle of this type of device is similar to that of a two-pole motor. The stationary coils on the field poles, "O" and "P", are connected to the running generator. The frequency of the current supplied to these coils will therefore be constant.

The movable coils, "A" and "B", are mounted on a shaft or rotor, at right angles to each other. The coil "A" is connected in series with a resistor, and coil "B" in series with a reactor. The two coils, with their resistance and reactance, are then connected in parallel and across one of the phases of the "incoming generator".

The current flowing in coil "B" will be approximately 90° out of phase with that in coil "A", because of lagging effect produced by the reactance coil in series with coil "B". This phase displacement of the currents produces a sort of revolving field around the rotor winding of the movable coils.

Let us assume that, at a certain instant, the current which is being supplied to the stationary field coils by the running generator reaches its maximum value at the same time as the current in the rotor coil "A", which is supplied from the incoming generator.

We shall assume also that at this instant these currents are both of the proper polarity to set up fluxes in the same direction, or from left to right between the field poles "O" and "P", and also from left to right through the center axis of the coil "A". Then these lines of force will tend to join together or line up with each other and cause the rotor to assume the position shown in the diagram.

If the frequency of the two generators remains the same, and if they are in phase, the rotor will remain in this position and the pointer will indicate that the machines are in synchronism.

If the maximum value of the current from the

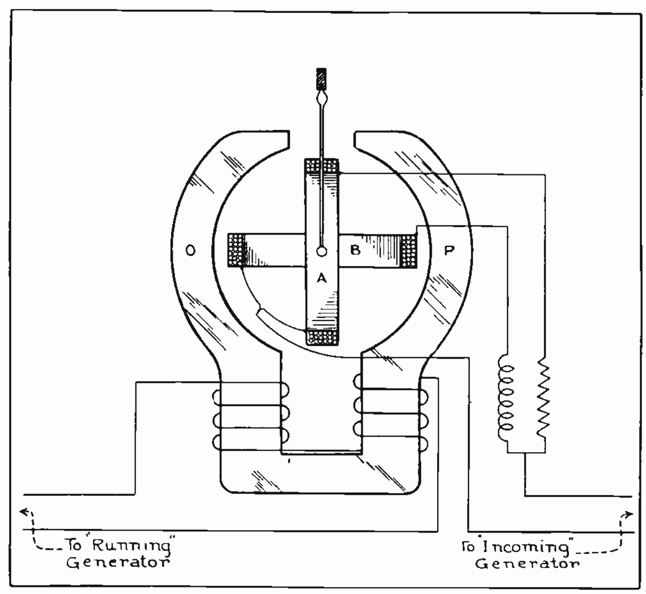

Fig. 75. The above diagram shows the important parts and illustrates the principles of a synchroscope. This diagram also shows the connections of the coils to the "running" and "incoming" generators.

running generators occurs about ¼ of a cycle or 90° later than the maximum value of the current from the incoming generator, then the current in the field poles will be in phase with the current in the rotor coil "B"; because the current through this coil is lagging approximately 90°, due to the inductance in series with it.

When the maximum flux and current occur at the same time at the field poles "O" and "P" and in the movable coil "B", this will cause the flux of coil "B" to line up with that of the field poles, and will cause coil "B" to turn into the position now occupied by coil "A" in the diagram.

If the angle of phase difference between the maximum currents of the two generators becomes still greater, the pointer will move a still greater distance from the point of synchronism.

82. SYNCHROSCOPE SHOWS WHICH MACHINE IS RUNNING TOO FAST

If the incoming generator is operated a little slower and at lower frequency than the running machine, the needle will move to the left; and when the current of the incoming machine drops 360° behind that of the running generator, the pointer will have made one complete revolution to the left.

If the incoming machine is rotating faster and producing higher frequency than the running generator, the pointer will revolve to the right, and the faster the pointer revolves, the greater is the difference in speed and frequency between the two machines.

Fig. 76 shows a synchroscope for switchboard mounting. The left side of its scale is marked "slow", and the right side marked "fast", with arrows to show the direction of rotation of the pointer for each condition. These terms marked on the scales of such instruments refer to the incoming machine.

Some types of synchroscopes have an open face or glass cover over the entire front, so that the entire pointer is in full view at all times. In other cases, the pointer moves behind a transparent scale such as shown in Fig. 76. These instruments have a small lamp located behind the scale, so that the pointer can be seen through the scale as it passes across the face of the meter.

This lamp, however, is lighted only when the two generators are nearly in phase with each other. This will be explained in a following paragraph.

Whether the synchroscope uses a lamp or not, it indicates that **the machines are in synchronism only when the pointer comes to rest over the dark spot at the top center of the scale.**

83. SYNCHROSCOPES WITH LAMPS

The diagram in Fig. 75 is for a synchroscope of the type on which the needle revolves in plain view around the open face of the meter, when the generators are operating at different frequencies.

The pointer of the meter shown in Fig. 76 does not revolve clear around, but only swings back and forth behind the scale when the machines are out of phase. But as the lamp behind the scale and pointer lights up only when the pointer is passing the lamp and dark spot on the scale, the pointer appears to be rotating either to the right or to the left. In this manner, this type of meter also indicates whether the incoming machine is running slower or faster than the running machine.

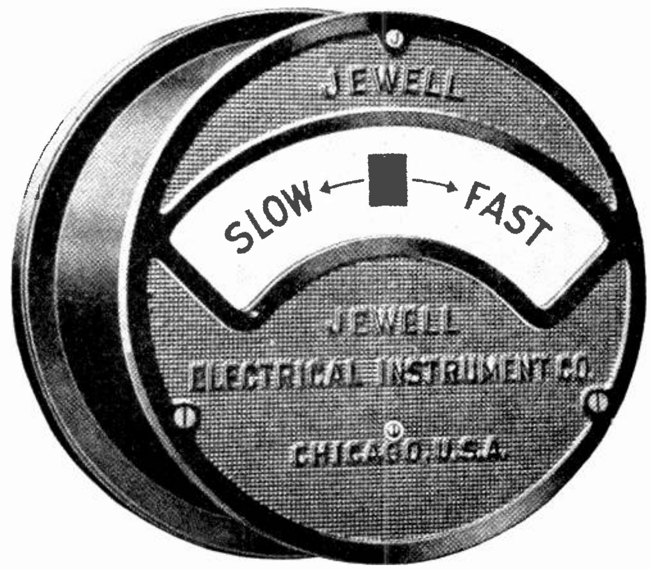

Fig. 76. Switchboard type frequency meter. With this type of instrument the pointer swings back and forth behind a transparent scale when the machines are out of phase.

Fig. 77 shows the inside of a synchronscope of this type and Fig. 78 shows the connection of its coils and also the transformer which operates the lamp.

The stationary coils, "C" and "C-1", are connected in series with a resistor and then across the busses of the running machine. The movable coil, "M" is connected in series with a resistor, "R", and a condenser, "X", and then across the busses of the incoming machine.

When the two generators are in phase the movable coil holds the pointer in a vertical position, but when the machines are out of phase the pointer will swing back and forth with a speed proportional to the amount of difference between the generator frequencies.

If the generators are running at the same frequency, but just a few degrees out of phase, the pointer will stand at a point a little to the left or right of the mark on the scale.

The lamp used with these synchroscopes is caused to light up and go out by being connected to the secondary of a small transformer which has two primary coils, one of which is connected to the running machine and the other to the incoming machine.

These primary coils are so wound that, when the machines are in phase opposition, the flux of the two coils joins around the outer core of the transformer, leaving the center leg idle, and the lamp dark.

When the two machines are in phase or nearly so, the fluxes of the two primary coils oppose each other and set up sufficient flux in the center leg of the core to induce a voltage in the secondary coil and light the lamp. Therefore, the lamp will light when the machines are in phase and will go dark when the machines are 180° out of phase.

A. C. generators can also be synchronized with a lamp bank, as will be explained in a later section, but the synchroscope is a more convenient and reliable device and it is practically always used for synchronizing alternators in power plants.

As it is not practical to synchronize and parallel more than one incoming generator at a time, one synchroscope can be used for several generators connected to a large switchboard. The synchroscope is frequently mounted on a hinged bracket or arm at the end of the switchboard so it will stand out where it can be seen by the operator from any point along the board.

In larger power plants a synchroscope with a very large face or dial is used in this manner, so it is plainly visible to operators. More complete instructions on paralleling generators by means of synchroscopes will be given in a later section.

Most synchroscopes have their coils wound for operation on 110-volt circuits, but external resistors can be used with them for connecting the instruments to 220 or 440-volt circuits. When they are used with generators of higher voltages, potential transformers are used to reduce the voltage to the instrument.

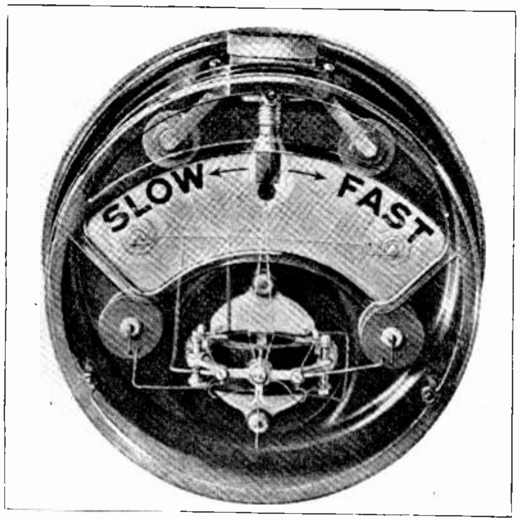

Fig. 77. This view shows the inside of a synchroscope and the arrangement of the various parts, including the lamp and meter coils.

84. INSTALLATION AND CONNECTIONS OF SYNCHROSCOPES

When installing and connecting a synchroscope, care should be taken to see that the proper terminals of the resistor and reactor are connected to the similarly marked terminals on the instrument. It is very easy to make mistakes in these connections, if they are not very carefully made.

The synchroscope, when shipped from the factory,

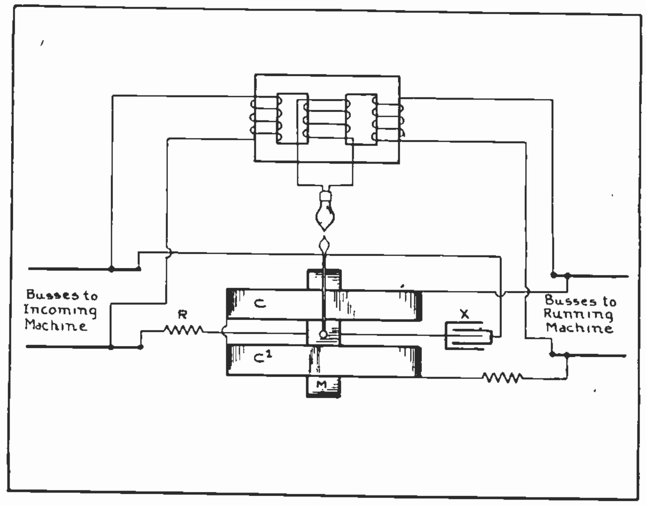

Fig. 78. This diagram shows the important parts and connections of a synchroscope similar to the one shown in Figs. 76 and 77.

has usually been tested and is packed in good condition. Therefore, if it doesn't operate correctly after it has been installed and connected, the fault is probably not in the meter, and the external wiring should then be checked over very carefully.

If the meter develops no torque, the trouble may be in the connections from the incoming generator. In this case the circuits through the resistor and reactor should be tested for opens, and the circuits through the meter should also be tested.

If the meter rotates but develops very little torque, the trouble may be in the connections from the running generator and its voltage and connections should be checked. A pair of test lamps can be used to determine whether the synchroscope is operating properly or not. If the lamps are connected to burn brightly when the two machines are in synchronism, and the synchroscope doesn't indicate synchronism at the same time the lamps do, the cause is probably wrong external connections, or the pointer may be displaced on the shaft.

Disconnect the meter from the generator busses and connect both elements to a single-phase circuit of the proper voltage. If the pointer now stands in vertical position, the meter is correct and the external connections must be checked.

If the instrument indicates synchronism when the two generators are 180° out of phase according to the lamp test, then reverse the two leads from the running generator. If the synchroscope rotates slowly when the generators are operating at widely different speeds and rotates rapidly when the generators are operating at nearly the same speed, the incoming generator may be connected to the running machine terminals of the meter.

The foregoing material on various types of A. C. meters, of course, does not cover every meter made, but does cover the more common types and the general principles on which they operate.

A good understanding of these principles and the applications of the various meters explained will be of great value to you in most any branch of electrical work, and will be very helpful in choosing proper meters and installing and testing them on various jobs.

Always remember when handling or working with electric meters of any kind, that they are usually very delicate in construction and should never be bumped or banged around Even slight jars may damage the jeweled bearings, shaft points, or some part of the moving element.

Connecting instruments to circuits of too high voltage or too heavy current for the range of the meter, will often bend the pointer or damage the moving element, and possibly burn out the coils.

Always try to appreciate the great convenience and value of electric meters for measuring the values of electric circuits, and handle these instruments intelligently and carefully on the job.

Intelligent selection of the proper meters for new electrical installations, or for old ones that do not have proper or sufficient meters, may often result in a promotion for you.

So give this subject proper consideration, and always handle any meters you may have to work with, in a manner that will be a credit to yourself and your training.

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ESTABLISHED 1899

ALTERNATING CURRENT
AND
A. C. POWER MACHINES

Section Three

A. C. Generators
Types, Construction Features, Cooling
Field Excitation, Exciter Generators and Connections
Alternator Voltage Control, Automatic Regulators
Operation and Paralleling
Phasing Out and Synchronizing
Starting Alternators, Adjusting Load
Shutting Down

ALTERNATING CURRENT GENERATORS

As most of the electrical power generated is alternating current, the operation and care of A. C. generators, or **alternators** as they are commonly called, is a very important subject. This section will deal principally with the common types of alternators; their construction, operation, and care.

The windings used in alternators and the principles by which they generate alternating voltage have been covered in the sections on Armature Winding and in Alternating Current, Section One.

Alternators are made in sizes ranging from the small belt-driven or engine-driven types of from 1 to 50 kv-a. up to the mammoth turbine-driven units of over 200,000 kv-a.

Alternators can be divided into the following classes: (A) Revolving armature or revolving field types: (B) Vertical or horizontal types; (C) Turbine or engine types.

85. REVOLVING FIELD ALTERNATORS

Practically all A. C. generators of over 50 kv-a. capacity are of the revolving-field type, because this type of construction permits the generation of much higher voltages in the stationary armature windings, and also because it eliminates the necessity of taking high-voltage energy from a revolving member through sliding contacts. This greatly simplifies the construction of the machine and reduces insulation difficulties.

Revolving-field alternators are commonly made to generate voltages as high as 13,200, and some are in operation producing voltages of 22,000 directly from their stator windings. Alternators can now be constructed to produce voltages as high as 36,000. The generation of such high voltages makes possible very economical transmission of this energy, and also reduces the necessary winding ratio of transformers when the voltage is to be stepped up still higher for long distance transmission.

At the left in Fig. 79 is shown the **stator,** or stationary armature, of an alternator. The **rotor,** or revolving field, which has been removed from the stator, is shown at the right. Note the stator coils or windings which are practically the same for alternators as for A. C. induction motors.

These windings were thoroughly described, both as to construction and connections, under Three-Phase Stator Windings in the Armature Winding Section.

Note also the construction of the revolving field element and the manner in which the poles are mounted on the spider. The collector rings, through which the low-voltage direct current is passed to the field coils, can be seen at the end of the rotor.

Some of the smaller A. C. generators have revolving armatures which are wound very similarly to those for D. C. generators, and have connections brought out to slip rings so the generated energy can be transferred from the revolving armature to the line by means of these slip rings and brushes.

However, many of the smaller alternators are also built with revolving fields. Fig. 80 shows a belt-driven alternator of 125 kv-a. capacity, with a revolving field and stationary armature. This generator is driven at 900 R.P.M. and produces three-phase, sixty-cycle energy at 2300 volts. Note the three leads which are brought out from the stator for permanent connection to the switchboard or line when the machine is installed. In this manner the load current flows directly from the stationary armature to the line without any slip rings or sliding connections in the circuit. Note the D. C. exciter-generator which is attached directly to the end of the shaft of this alternator.

Fig. 81 shows the revolving field for a small alternator of the type shown in Fig. 80. Note carefully the construction of the field poles on this rotor, and also the slip rings and D. C. exciter-armature on the end of the shaft.

The direct current energy required to excite the field of an A. C. generator is very small in comparison with the A. C. output of the machine. **This energy for excitation varies from three-fourths of one per cent. to two and a half per cent. of the total capacity of the alternator.**

It is easy to see, therefore, that the revolving field will require much smaller and lighter conductors than a revolving armature would; and also that the handling of this smaller amount of energy through

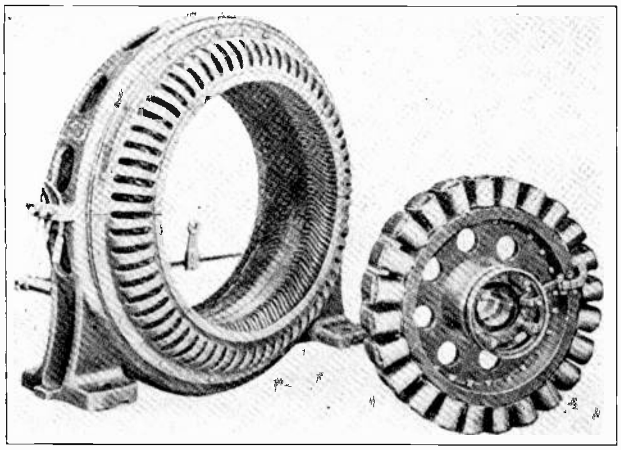

Fig. 79. Above are shown the complete stator of an A. C. generator on the left and the revolving field or rotor on the right. The field coils on the rotor are excited with direct current and revolved within the stator to generate alternating current in its windings.

brushes and slip rings at low voltage, is a much simpler proposition than to handle the total load current of the machine at the high voltages used on modern alternators.

Keep in mind that it makes no difference in the nature or amount of voltage generated by the machine whether the field poles revolve past the stationary armature conductors or the armature conductors revolve past the stationary field poles. As long as the same field strength and speed of motion are maintained, the cutting of the lines of force across the conductors will in either case produce the same voltage and the same frequency.

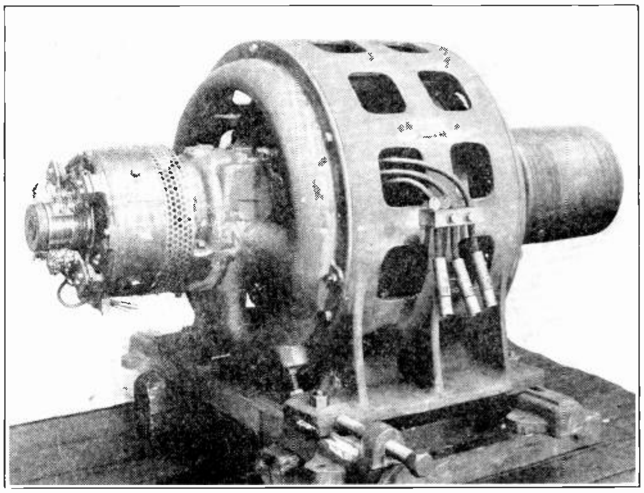

Fig. 80. This photo shows a 125 kv-a. alternator of the horizontal belt-driven type. Note the D. C. exciter-generator which is direct connected to the left end of the shaft. (Photo Courtesy Allis Chalmers Mfg. Co.)

86. VERTICAL TYPE AND HORIZONTAL TYPE ALTERNATORS

The terms vertical and horizontal as applied to A. C. generators refer to the position of the shaft. Belt-driven alternators, or generators that are connected directly to steam engines, are usually of the horizontal-shaft type. The generator shown in Fig. 80 is of the horizontal type.

Large steam-turbine-driven generators are also more commonly made in the horizontal types, although some of these are in operation which have vertical shafts.

Water-wheel generators are more commonly made in the vertical type, as this construction allows the generator to be placed on an upper floor, with the water-wheel on a lower level and attached to the generator by means of a vertical shaft.

This reduces the danger of moisture coming in contact with the generator windings due to any possible leakage or dampness around the water-wheel.

Fig. 82 shows a large, vertical type, water-wheel-driven generator. This machine has a capacity of 18,750 kv-a. and produces 60-cycle alternating current at 6600 volts. Machines of this type usually operate at quite low speeds, this particular one having a normal speed of 112½ R.P.M.

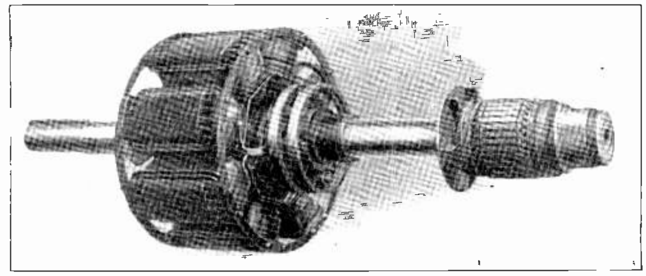

Fig. 81. This view shows the construction of the rotor or revolving field of an alternator similar to the one shown in Fig. 80. Examine its construction carefully and note the position of the collector rings and exciter-armature on the shaft.

Note the D. C. exciter-generator mounted on top of the shaft above the thrust bearing and main support members of the generator frame. The water-wheel attaches to this generator at the coupling which is shown on the lower end of the shaft.

Horizontal-type generators usually present a much simpler bearing problem, as the horizontal shaft lies in simple sleeve-bearings which support the weight of the revolving field at each end of the shaft.

Vertical-type generators require special thrust-bearings to support the weight of the shaft and rotor, and also a set of guide bearings to keep the rotor in proper alignment within the stator core.

Vertical-type machines require less floor space, which is one advantage in their favor where the power plant must be as small as possible.

87. TURBINE TYPE AND ENGINE TYPE ALTERNATORS

The terms "turbine" and "engine" type as applied to alternators refer to the type of prime mover by which the alternator is driven. As there is considerable difference between the speeds of ordinary reciprocating steam engines and those of steam tur-

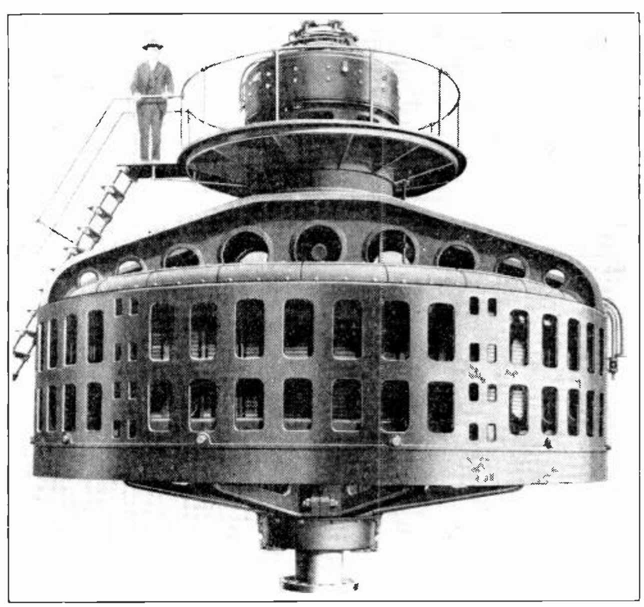

Fig. 82. Large vertical type alternator for water-wheel drive. The stator core and windings of this machine lay in a horizontal position just inside the lower frame work, and the field poles revolve on the vertical shaft within the stator. (Photo Courtesy Allis Chalmers Mfg. Co.)

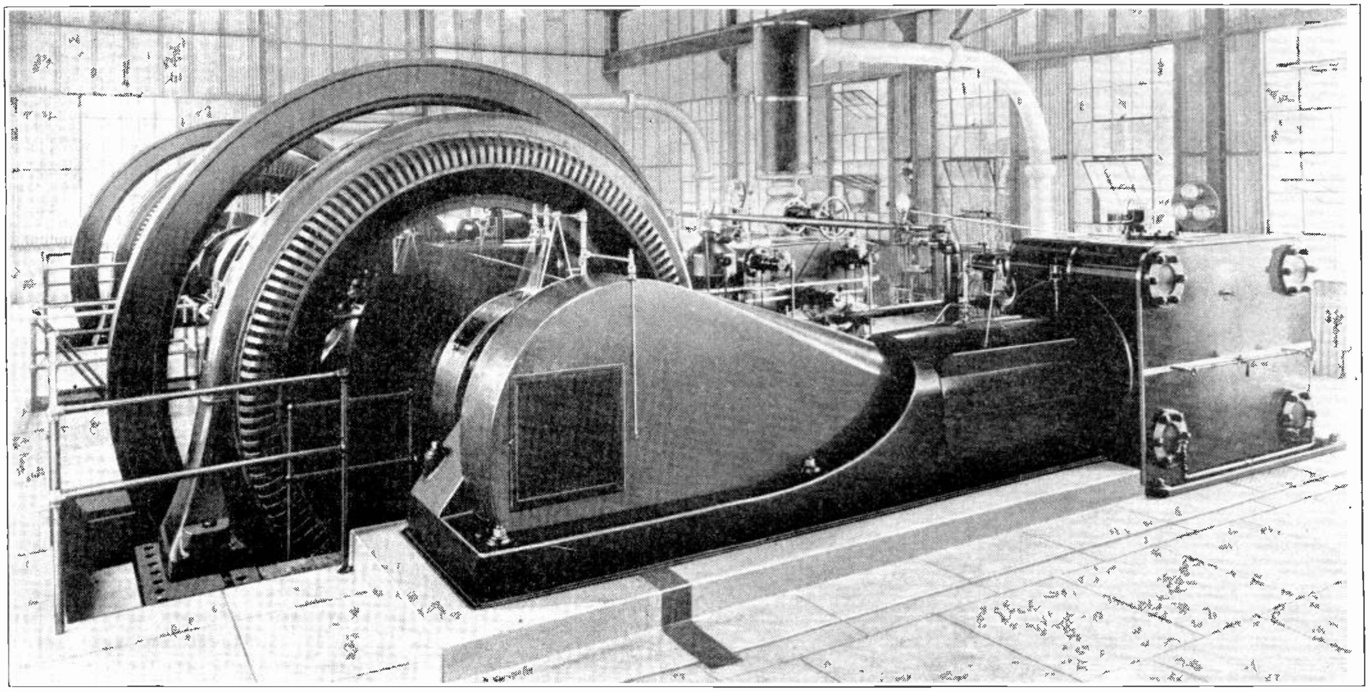

Fig. 83. This photo shows a view in a power plant equipped with horizontal type steam-engine-driven alternators. These alternators are made with large diameters because of the relatively low speed at which they are driven. (Photo Courtesy Allis Chalmers Mfg. Co.)

bines, the generators designed for engine drive are of considerably different shape and construction than those designed for high-speed turbine drive.

Engine-driven alternators are usually of quite large diameter and narrow in width from one side to the other of the stator core. The rotors for these machines usually have a rather large number of field poles, in order to obtain the proper frequency at their low operating speeds.

Fig. 83 shows a horizontal-type engine-driven alternator of 1000 kv-a. capacity, and gives a good general idea of the shape and construction of these machines. Note the large fly-wheel used in connection with such alternators to maintain a more even speed in spite of the pulsations delivered by the piston of the engine.

Steam-turbine-driven generators, or turbo-alternators as they are commonly called, are usually made with much smaller diameters and greater in length than the engine-type generators are. The very high speeds at which steam turbines operate makes necessary the small diameter of the revolving field of the generator, in order to reduce centrifugal stresses.

These higher operating speeds also make possible the generation of ordinary 60-cycle energy with a very small number of field poles.

Turbine-driven generators are commonly made with two or four poles on the revolving field. Fig. 84 shows a large steam-turbine-driven alternator of 50,000 kw. or 62,.500 kv-a. capacity. The generator is on the left in this view and the steam turbine on the right. The two are directly connected together on the same shaft.

This alternator is completely enclosed in an air-tight casing to keep out all dirt and moisture from its windings, and to allow cooling by forced air circulation within this casing.

88. CONSTRUCTION OF ALTERNATORS. ARMATURES

Regardless of the type or construction of the alternator, the two principal parts to be considered are the armature and the field. The main A. C. winding, whether it is placed on the rotor or in the stator, is usually referred to as the armature; and, as previously mentioned, these armature windings for ordinary A. C. generators are practically the same as those for the stators of induction motors. In fact, the same winding can be used for either a motor or generator, if the squirrel cage is exchanged for a revolving field with the proper number of poles, or vice versa.

On large machines there are enormous magnetic stresses set up between the conductors of the winding when the generators are heavily loaded or during times of sudden surges due to overloads or short-circuits. For this reason, it is necessary to securely anchor or brace the coils, not only by slot wedges but also by using at the coil ends, special supports which are rigidly connected to the stator frame.

The coils are securely tied or wrapped to these braces or supports and in some cases are mechanically clamped down on the supports to prevent distortion or warping of the coils due to magnetic stresses set up by the flux around them.

The view on the left in Fig. 85 shows the frame of a turbine-driven alternator with one of the first stator punchings or core laminations in place. This view shows the manner in which these core laminations are fitted in the stator frame and held in place by the dovetail notches in the frame.

When the complete core is assembled, the laminations are also held more firmly together by the use of clamping rings and bolts which apply pressure at the ends of the stator core.

The view at the right in Fig. 85 shows the same stator with the core completely assembled and the windings in place. Note the heavy connections which are made between the phases and coils of the winding and also the manner in which these connections are rigidly secured to the end of the stator core.

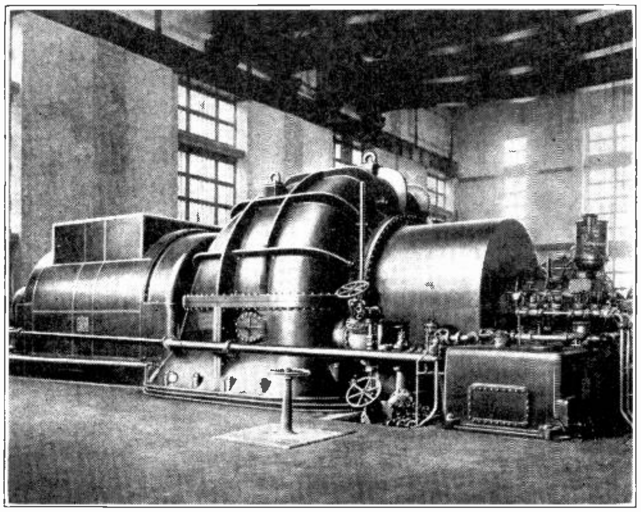

Fig. 84. Large steam-turbine-driven alternator. The turbine with its control mechanism is on the right. The alternator is enclosed in the air-tight casing at the left. This unit is typical of hundreds of great steam-driven generators in use in modern power plants throughout this country. (Photo Courtesy General Electric Co.)

Fig. 86 shows an excellent view of the end of the winding in a large turbine-driven generator, and shows clearly the method of bracing and tying the coils in place. Note the comparatively small diameter and great length of the stator openings on the machine shown in Figs. 85 and 86.

The armature coils on large alternators are usually made of heavy copper bars and consist of only a few turns to each coil. These coils are heavily insulated according to the voltage of the machine, and are securely wedged into the slots.

Spaces or air ducts are left at intervals throughout the stator when the laminations are assembled, to allow free circulation of the cooling air throughout the windings.

89. FIELD CONSTRUCTION

The field of an A. C. generator is constructed very much the same as the field of a D. C. generator, except that the field of an alternator is usually the revolving element. Low-speed alternators of the large diameter engine-driven types usually have the field poles mounted on a spider or wheel-like construction of the rotor, as shown in Fig. 79.

Fig. 81 also shows the mounting of the field poles on a smaller rotor of the solid type which is used for a small diameter, medium-speed alternator.

The poles consist of a group of laminations tightly clamped together and equipped with a pole-shoe, or face, of soft iron. They are attached to the rotor core or spider, either by means of dovetail ends and slots or by means of bolts.

Fig. 87 shows several views of field poles of the dovetail type. These views also show the pole shoes and the rivets which hold the laminations together. The coils for field poles of this type may be wound with either round or square wire, or thin, flat, copper ribbon of the type shown in Fig. 88.

Field poles and coils of this type are sometimes called "spool wound", because of the shape of the poles and the manner in which the coils are wound on them.

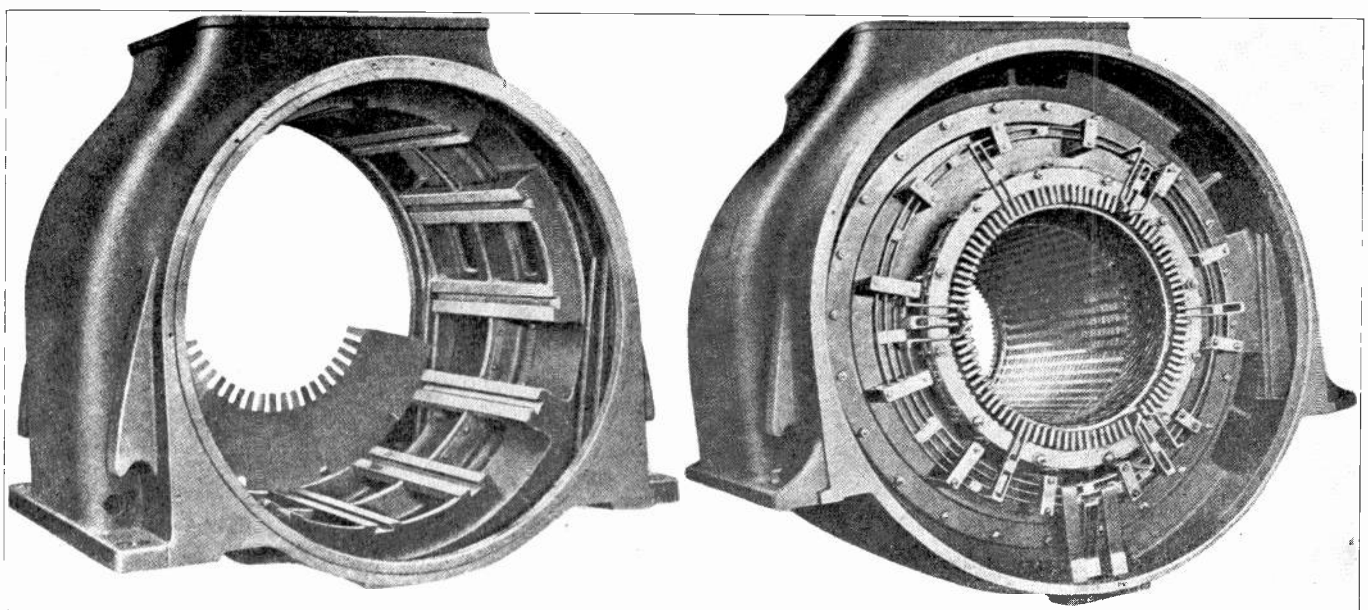

Fig. 85. The above two views show very clearly the method of construction of the stator core and windings of high speed steam-turbine-driven alternators.

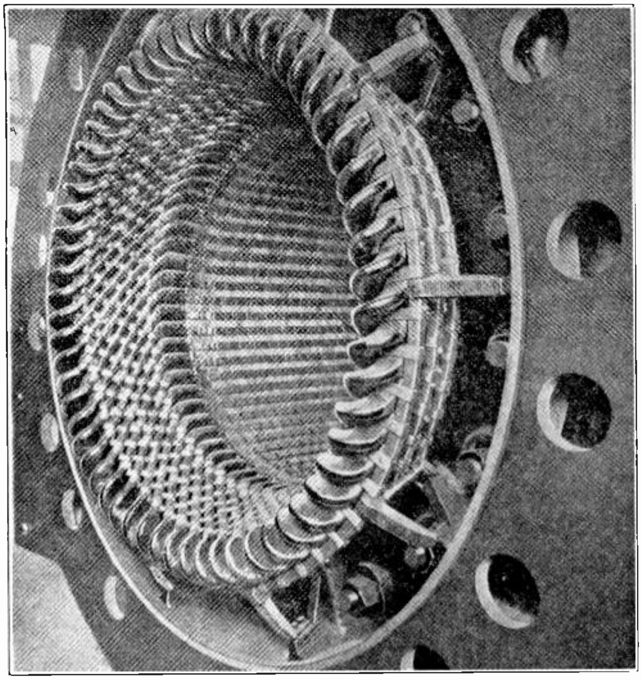

Fig. 86. This photo shows the end of a stator winding for a high speed turbo-alternator. Note the rigid bracing of the coil ends.

The field coils are connected either in series or in series-parallel groups, according to the size of the machine and the exciter voltage which is applied. They are always connected to give alternate north and south poles around the entire field. Alternator fields always have an even number of poles.

On high-speed turbine-driven alternators which have long rotors of narrow diameter it would be very difficult to construct field poles of the "spool wound" type, and also extremely difficult to hold the coils in place because of the great centrifugal force at these high speeds. For such machines the field coils are usually wound in the slots cut in the surface of a long, solid field rotor or core.

Fig. 89 shows a two-pole rotor of this type, in which the field coils can be plainly seen at the left end of the slots. These coils are wound with strap or bar copper. When the rotor is completed, a metal casing or sleeve is placed over both ends of the coils as shown at the right end of this rotor. This sleeve protects the coils from damage or mechanical injury and also holds them securely in place and prevents them from being thrown or bent outward by the high centrifugal force exerted upon them during operation.

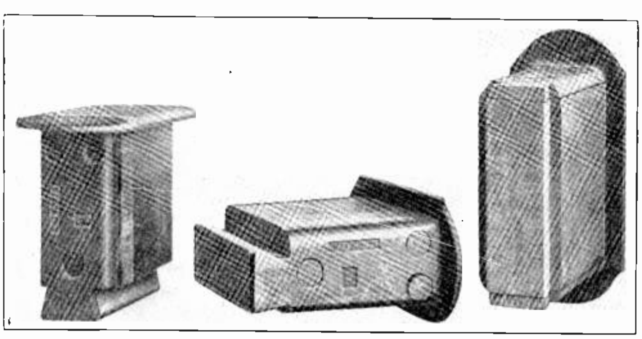

Fig. 87. Several views of laminated field poles such as commonly used in revolving field alternators.

Fig. 90 shows a closer view of the end of a rotor of this type, on which the slip rings and ventilating blades can be clearly seen. This type of rotor construction provides a very rugged field element and very secure mounting of the coils and is, therefore, ideally suited to the very high speeds at which steam-turbine alternators are operated.

90. COOLING OF GENERATORS

All electrical equipment produces a certain amount of heat in proportion to the losses which take place within the windings. Large A. C. generators produce considerable heat, even though their efficiencies often approach 98%. In the enormous sizes in which generators are built today the cooling of these machines becomes a serious problem.

The heat must be removed or carried away from the windings as rapidly as it is created or the windings would soon overheat to a point where the insulation would be damaged. As the resistance of copper conductors increases with any increase in temperature, the efficiency of the machine would also be reduced by allowing it to operate at temperatures higher than normal.

Natural air circulation is not sufficient for effective cooling of the windings of these large machines, as it is with smaller D. C. and A. C. generators. Therefore, it is necessary to use one of the several forms of artificial cooling or forced ventilation.

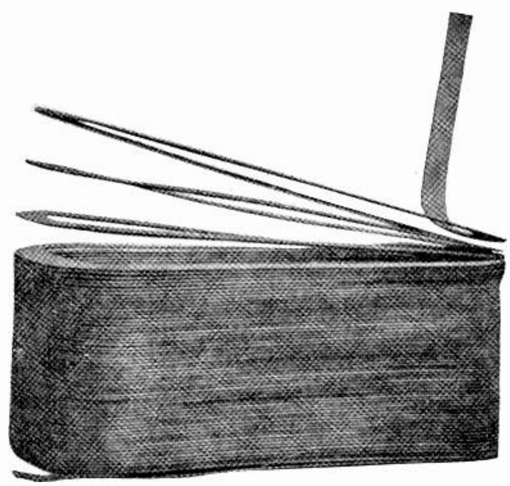

Fig. 88. Field coil which is wound with thin copper strip, making a coil which is very compact and easily cooled.

One very common method of cooling is to completely enclose the generator in a housing, such as shown on the machine in Fig. 84, and force a blast of air under low pressure through this housing and the machine windings. The air used for this purpose is first washed with a spray of water to cool it and clean it of all dust and dirt, and then the air is dried before being passed through the generator windings.

This clean air is then kept dry and is recirculated through the generator over and over again, being

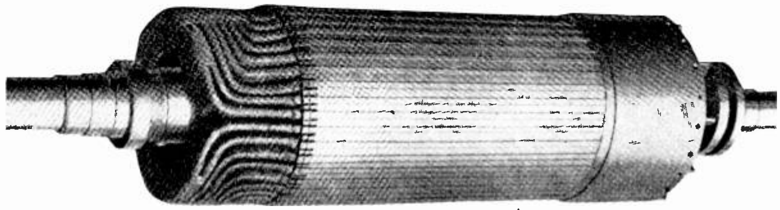

Fig. 89. This photo gives an excellent view of a high speed field rotor such as commonly used in turbine-driven alternators. Note how the field coils are placed in slots in the solid rotor so that when they are excited with D.C. they will create two field poles on opposite sides of the rotor. (Photo Courtesy Allis Chalmers Mfg. Co.)

cooled each time it leaves the machine, by being passed over a set of cold water pipes.

It is of the greatest importance that this ventilating air be kept circulating constantly through large alternators during every moment of their operation, and also that the air be kept clean and dry.

Some other gases are more efficient than air for carrying off the heat from machine windings. Hydrogen gas is being successfully used for this purpose. Because of its efficiency in absorbing heat from the windings and transferring it to the cooling pipes through which the gas is circulated outside of the generator, the use of hydrogen in this manner makes possible increased efficiencies and reduced sizes of alternating current machines.

Hydrogen being an explosive gas, it is necessary to eliminate all possibility of its becoming ignited around the generator; otherwise an explosion and serious damage would result.

Large alternators are usually equipped with thermometers or electrical temperature indicators to show the temperature of their armature windings at all times during operation. Many large high-speed alternators have water-cooled bearings, with water circulating through passages in the metal around the bearings, to carry away the heat.

91. ALTERNATOR FIELD EXCITATION

The field of an alternating current generator is always excited or energized with direct current and in this manner constant polarity is maintained at each pole. As alternators do not produce any direct current themselves, they cannot be self-exciting, as many D. C. generators are.

The direct current for excitation of alternator fields is produced by a separate D. C. generator, known as the **exciter generator.** The exciter machine may be belt-driven from a pulley placed on the shaft of the main alternator, or it may be directly connected and driven by the end of the alternator shaft as on the machines in Figs. 80 and 82.

In some cases in large power plants the exciters are driven by separate prime movers. Sometimes one large exciter-generator is used to furnish direct-current field energy for several alternators, each of which obtains its field current from the exciter bus.

In other cases, there may be a number of exciter-generators which are all operated in parallel to supply the exciter bus with direct current; and any or all of the alternators can obtain their field current from **this bus.**

Exciter-generators are usually of the compound type and of a voltage ranging from 110 to 250 volts. It is not necessary to use high voltage for field excitation, as this current is only used to produce magnetic flux, the strength of which is determined by the number of ampere turns on the field poles.

The direct current from the exciter generator or busses is conducted to the revolving field poles of the alternator through brushes and slip rings, as previously explained. These slip rings can be plainly seen on the revolving field units shown in Figs. 81 and 89.

92. CONNECTIONS OF EXCITER AND ALTERNATOR FIELD CIRCUIT

Fig. 91 shows the connection diagram and circuit of an exciter-generator connected to a three-phase alternator. This alternator has four poles on its revolving field and in this case all of the poles are connected in series.

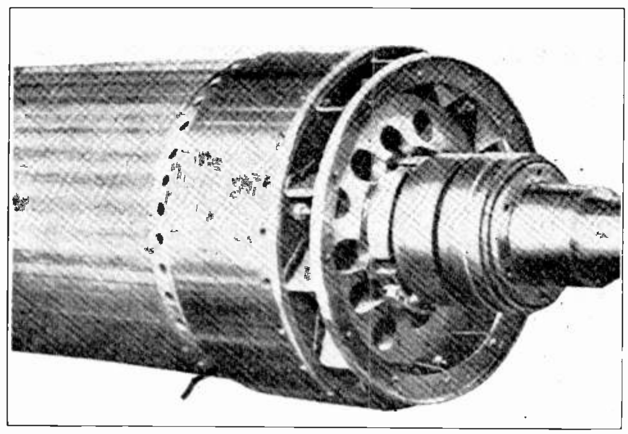

Fig. 90. End-view of high speed field rotor showing shield ring over the coil ends and also showing ventilating blades and slip rings.

The stator winding is of the ordinary type which has been previously described in the section on A. C. Armature Windings, and in this diagram it is simply shown as a continuous winding around the stator, having three line leads which are connected to points 120 degrees apart around the winding.

When the field of this alternator is excited with direct current and the poles revolved so their flux cuts across the conductors of the stator winding, three-phase alternating current will be generated and supplied to the line or busses.

If this four-pole machine has its field revolving at 1800 R.P.M., the frequency of the generated A. C. will be 60 cycles per second, according to the formula given in Article 4 of A. C. Section One.

The exciter shown in this figure is a compound-wound D. C. generator and has its voltage controlled by means of a shunt-field rheostat, R. The exciter voltage can be controlled either by manual operation of the field rheostat or by an automatic voltage regulator in connection with the field rheostat. This regulator will be explained in later paragraphs and in this figure we shall consider the rheostat to be manually operated.

A voltmeter and ammeter are shown connected to the exciter circuit between the D. C. generator and the field discharge switch, S, of the alternator. They are connected at this point because it is desirable to know the exciter voltage before the field switch is closed, and also because of the high voltages which may be induced in the alternator field if the field discharge switch should accidently be opened while the alternator is operating in parallel with others.

The ammeter indicates the amount of field current which is being supplied to the alternator at any time, and furnishes an indication of the field strength and normal or unusual operating conditions in the alternator.

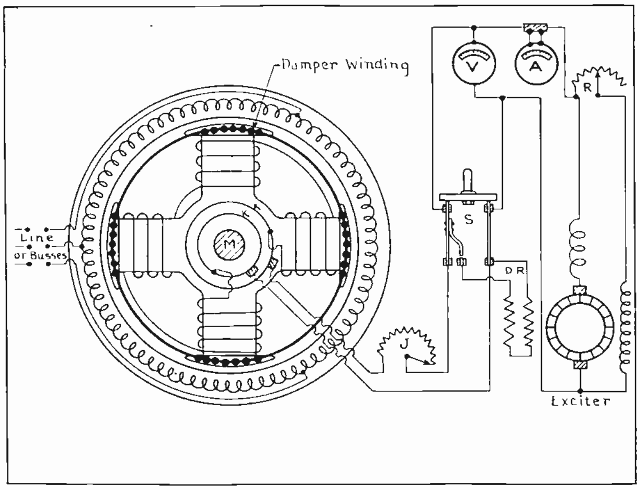

Fig. 91. This diagram shows the connections of the stator and rotor of a three-phase alternator with the exciter-generator, rheostats, meters, and field discharge switch.

93. FIELD DISCHARGE SWITCH

The field discharge switch is a special type of switch which has a third or auxiliary blade attached to one of the main blades and is arranged to make contact with an extra clip just before the main blades of the switch are opened, and also during the time that this switch is left with the main blades open.

This places the field discharge resistance, D. R., across the collector rings and field winding of the alternator when its circuit to the exciter is open. The purpose of this discharge resistance is to prevent the induction of very high voltages in the field winding when its circuit is interrupted and the flux allowed to collapse across the large number of turns of the field winding.

Placing this resistance across the field winding allows the induced voltage to maintain a current through this closed circuit for a short period after the switch is open. This uses up the self-induced voltage and magnetic energy of the field, and allows the current to die down somewhat gradually.

If the flux of the alternator field were allowed to collapse suddenly by completely opening the circuit, the induced voltage might be sufficiently high to puncture the insulation of the field windings and cause short-circuits or grounds between the winding and the core.

94. EXCITER AND ALTERNATOR RHEOSTATS

Between the field discharge switch and the slip rings is an alternator field rheostat, "J". This rheostat is used to obtain very fine and accurate adjustment of the alternator voltage, and its resistance is usually so proportioned that its full range of voltage operation is just equal to the change in voltage obtained by moving the arm of the exciter rheostat one point.

It is easy to see that the voltage of the main alternator can also be conveniently controlled by adjusting the voltage of the exciter generator. As the exciter voltage is varied, more or less current will be forced through the field winding. By the proper use of both the exciter field rheostat, R, and the alternator field rheostat, J, a wide range of voltage adjustment in very small steps can be obtained on the alternator.

For example, suppose that the exciter shunt field rheostat has 10 points, which will make it possible to obtain 10 voltage changes on both the exciter output and the alternator output. If the alternator field rheostat has 20 points, we can obtain 20 steps or variations in the alternator voltage between each two adjacent points of the ten-point exciter rheostat.

With this combination it is therefore possible to obtain 200 voltage variations, which will permit very accurate voltage adjustment of the alternator.

95. FACTORS GOVERNING VOLTAGE AND FREQUENCY OF ALTERNATORS

From the alternator field rheostat we follow the exciter circuit to the brushes which rest on the slip rings, K-K. The slip rings are mounted on the rotor shaft but are well insulated from the shaft and from each other. Leads are taken from these rings to the field coils. The slip rings and brushes form the sliding connection between the stationary part of the exciting circuit and the revolving alternator field.

Regardless of whether the alternator field is constructed with spool type coils on projecting poles as shown in Fig. 91 or with coils imbedded in the slots of the solid rotor as used on high-speed turbine generators, as long as direct current is passed through these coils a powerful magnetic field will be set up at each pole of the electro-magnets formed by the coils.

When the alternator field is thus excited or energized and is then revolved within the armature or stator core, it is evident that the lines of force from the field poles will be cut by the stationary armature conductors. In this manner a voltage is induced in the armature conductors and, as we have already learned, this voltage will be proportional to the number of lines of force in the field, and to the speed with which the field poles are rotated, as well as the number of conductors in series in the armature winding.

As the frequency of the alternator depends upon its speed and the number of field poles, we cannot vary the speed of the alternator to vary its voltage, as we can with direct current generators.

The frequency must be kept constant in order to maintain constant speed of the motors attached to the system, and if the speed of the alternator were to be varied it would, of course, change the frequency. For this reason, **the voltage of an alternator must be adjusted by means of the alternator field rheostat or the exciter field rheostat.**

The voltmeter in Fig. 91 is across the armature leads of the exciter generator and will show any variations in the voltage produced by the exciter when its rheostat is adjusted.

When once the setting of the alternator rheostat, J, has been established, the voltmeter will give somewhat of an indication of the variations brought about in the alternator field strength when varying the exciter voltage.

The ammeter provides a more accurate indication, because its readings will show the amount of current flowing through the alternator field with any adjustment or change in either the exciter or alternator rheostats.

96. CONTROL AND ADJUSTMENT OF ALTERNATOR VOLTAGE

It is often necessary to change the voltage produced by the armature of an A. C. generator while it is in operation, in order to compensate for voltage drop in the lines with increasing load on the system. In other words, when the load is increased, the added current flowing through the line will cause a greater voltage drop; and, in order to maintain constant voltage at the load, the alternator voltage should be increased.

We have already mentioned that the alternator voltage can be controlled either by manual operation of the rheostats by the plant operator, or by an automatic regulating device.

Manual or hand regulation is generally used only in small power plants which are not operating as a part of a large system.

The accuracy and uniformity of hand regulation depend upon the faithfulness and skill of the operator. This method is not usually satisfactory in large plants or on systems where there are frequent variations of considerable amounts in the load, because it requires almost constant attention on the part of the operators and even then doesn't prevent some voltage variation at the load.

It is very important to have constant voltage on most electrical machines and devices, in order to maintain their rated torque and speed. This is particularly true where any lighting equipment is connected to the system, because if the voltage is allowed to vary to any extent, it causes noticeable fluctuations in the brilliancy of incandescent lamps.

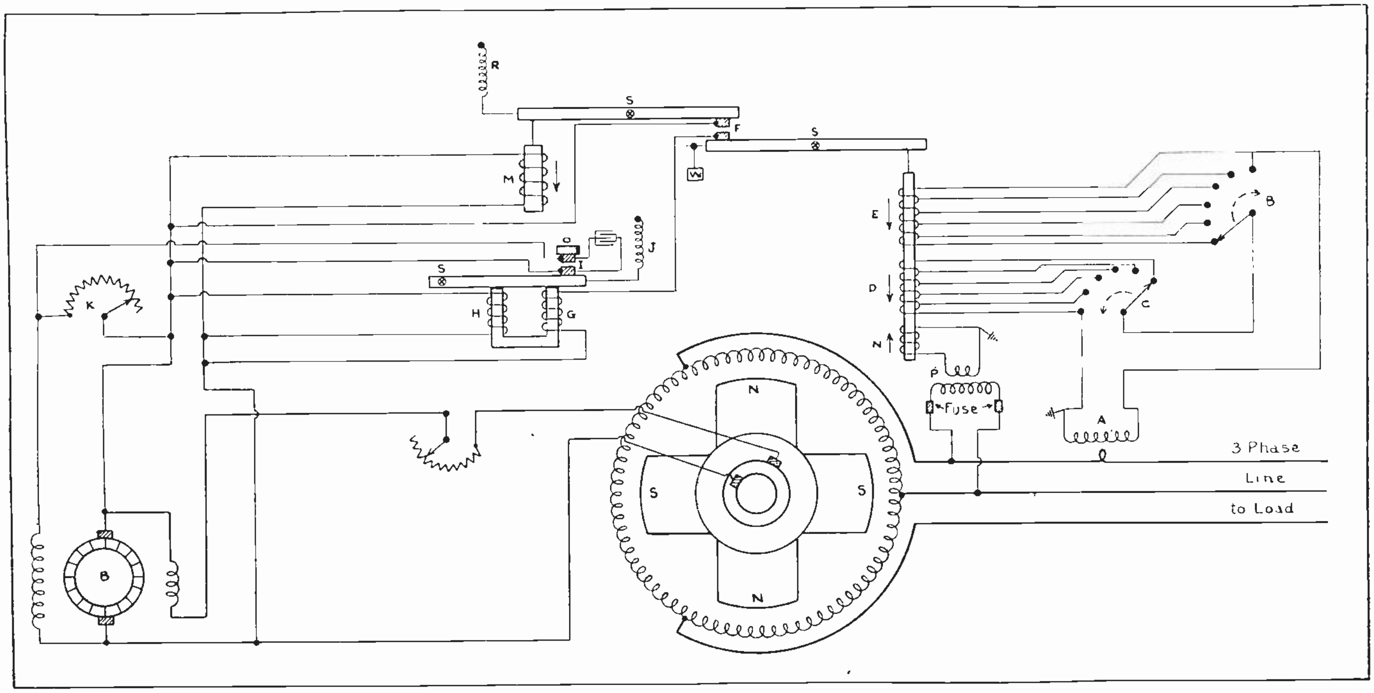

Fig. 92. The above diagram shows the wiring and illustrates the principles of a Tirrill automatic voltage regulator, properly connected to the exciter and line leads of a three-phase alternator.

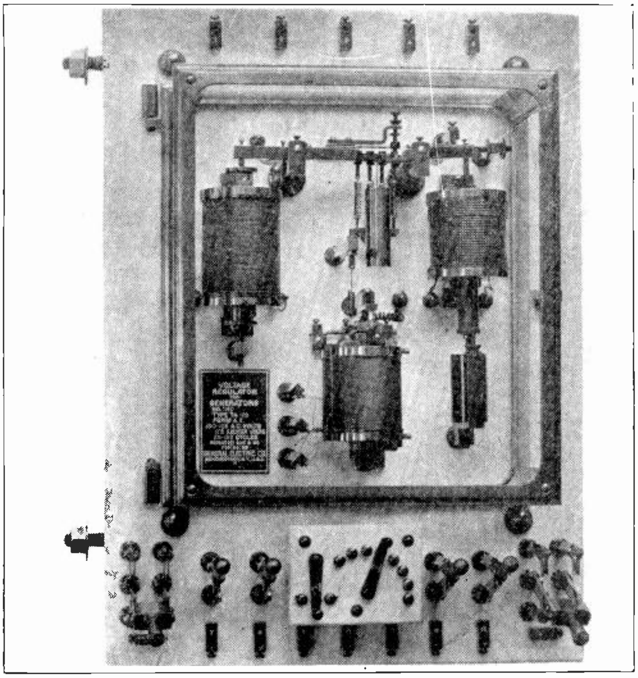

Fig. 92-A. This photo shows an automatic voltage regulator of a type similar to the one for which the wiring was shown in Fig. 92. and shows the arrangement of the solenoids and relays on the panel. (Photo Courtesy General Electric Co.)

97. AUTOMATIC VOLTAGE REGULATORS

To obtain more accurate and immediate voltage adjustment for all variations in load, automatic voltage-regulators are generally used in connection with the exciter field rheostat. One of the most common types of these devices is known as the Tirrill voltage regulator. This device automatically regulates the alternator voltage within very close limits by means of a set of relays which cut resistance in or out of the field rheostat of the exciter-generator.

The relays are operated by variations in the voltage and current load on the lines leading from the main alternator.

Fig. 92 shows the connection diagram of a Tirrill automatic voltage-regulator. If you will trace out each part of this diagram very carefully, you will be able to easily understand the operating principle of this device.

Whenever the load on the alternator is increased, this will increase the amount of current flowing in each wire of the three-phase line, and the current transformer, A, will have an increased current flow in its secondary winding.

The secondary of this transformer is connected through a set of multiple point switches, B and C, to the solenoid coils, D and E. When these two coils have their current increased, they tend to pull the plunger downward and operate the lever arm to close the contacts at F.

When the contact F is closed it completes a circuit through coil G of the differential relay which is energized by direct current from the exciter-generator. Coil H of this relay is connected directly across the exciter-armature and is normally energized at all times.

Coil G is so wound that when it becomes energized it neutralizes the magnetism set up in the core by coil H, and this allows the armature to release and be drawn upward by the spring, J, thus closing the contacts at I.

These contacts are connected across the exciter field rheostat, K, and can be arranged to short-circuit all or part of this resistance. When the resistance of this rheostat is cut out of the shunt field of the exciter it allows the exciter voltage to increase, thereby increasing the field strength and the voltage of the main A. C. generator.

If the A. C. generator voltage rises above normal, it will increase the voltage induced in the secondary coil of the potential transformer, P, thereby strengthening the solenoid coil, M, which will raise the plunger and open the contacts, F.

When the contact opens at F this de-energizes coil G of the differential relay, allowing the magnetism of coil H to draw the armature down and open contacts at I.

This removes the short-circuit from the exciter rheostat and places the resistance back in series with the shunt field. The contacts at F can also be opened by the coil M if the exciter voltage rises too high.

When using a regulator of this type, the exciter field rheostat K should be set at a point so that if it were used alone it would maintain a voltage slightly lower than that required by the system.

The automatic regulator will then short out the resistance of the rheostat often enough to maintain the voltage at its proper value. The arm which

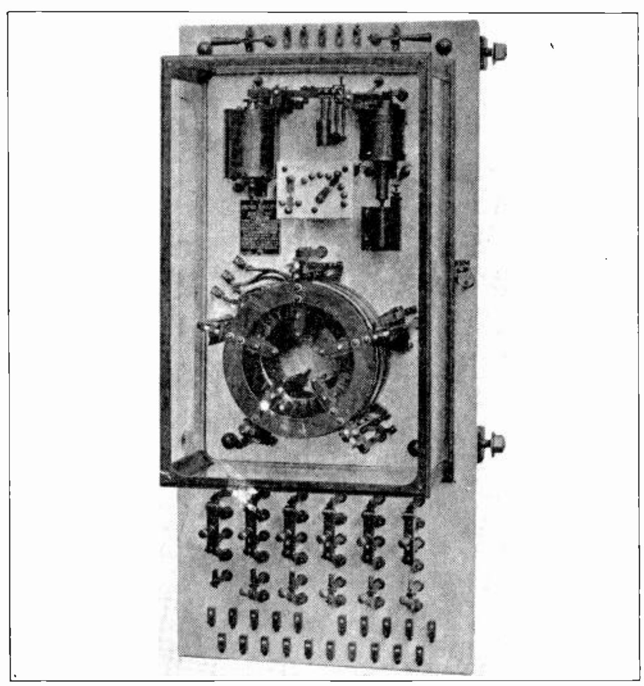

Fig. 92-B. Automatic voltage regulator for controlling the voltage of several alternators in parallel. (Photo Courtesy General Electric Co.)

operates the lower contact at F continually vibrates or oscillates, and opens and closes the contacts at frequent intervals during the operation of this device.

These contact arms are accurately balanced and adjusted by means of adjusting screws on the counter-weight, W, and the tension of the spring, R.

A condenser, O, is connected across the contacts I to reduce arcing and prevent burning and pitting of these contacts when they open and close the short-circuit on field rheostat K.

The relay armatures which operate the various contacts are pivoted at the points marked S. The switches, B and C, are used to vary the strength of the solenoid coils, E and B, and thereby adjust the regulator to operate at the proper amount of increased load current.

OPERATION AND PARALLELING OF ALTERNATORS

It is only in very few cases, such as in small isolated power plants, that a single A. C. generator is operated alone. Usually several A. C. generators are operated in parallel in the same plant, and in a great many cases a number of power plants generating A. C. are all tied together in parallel.

In our study of D. C. generators we found that it is absolutely necessary to have their voltages equal and polarities right if the machines are to be operated in parallel.

In order to operate alternators in parallel we **must have their voltages equal** and in addition to this, the machines must be properly **phased out** and **synchronized.**

These three conditions are the principal ones which must be observed before connecting any alternator in parallel with another.

You have already learned how to adjust the voltage of A. C. generators. Voltage adjustment, of course, can only be used to vary the voltage within a limited range above and below that of the normal voltage of the machine. Therefore, alternators must all be designed for the same voltage in order to operate successfully in parallel. Then the final adjustments can be made with the rheostats to exactly equalize the voltage.

98. PHASING OUT ALTERNATORS

"Phasing out" consists of identifying the phases of polyphase generators, in order to get the corresponding phase leads of two or more machines connected together. For example, the three-phase alternator, which is by far the most common, usually has the phases marked or designated A, B, and C. When connecting an alternator to one or more others, or to the busses in a power plant in which other generators are operating, each phase must connect to the corresponding phase of the busses or other alternator: A to A, B to B, and C to C.

Phasing out is usually necessary only when a machine is first installed or after some changes have been made in the connections of the windings of the machine. Once the generator has been properly phased out and the connections permanently made to the busses on the switchboard, it is not necessary to test the phases again unless changes are made in the generator or in the plant.

If a generator is disconnected even temporarily, the phases should be plainly and accurately marked, so that they can be connected back in the same manner when the machine is again attached to the busses or leads to the other alternator.

If an armature of an alternator has been rewound or if the connections have been changed in any way, the machine should always be phased out before reconnecting it to the busses or line.

Synchronizing is an operation which must be performed every time an A. C. generator is paralleled with other running machines. This will be explained in later paragraphs.

There are several methods that can be used for phasing out A. C. generators. Two of the most common are known as the **lamp-bank method** and the **motor method.**

Equally good results can be obtained with either method, and the choice of one or the other will usually depend upon the convenience or the adaptability of the available equipment.

99. LAMP-BANK METHOD OF PHASING OUT

Fig. 93 shows the connections and illustrates the principle of the lamp-bank method of phasing out alternators. In this diagram two alternators are shown properly connected and furnishing power to the busses and outgoing line. A third similar generator is shown suitably located and ready to be phased out and connected to the live busses. The lamps to be used in the phasing-out operation are shown connected around the oil switch.

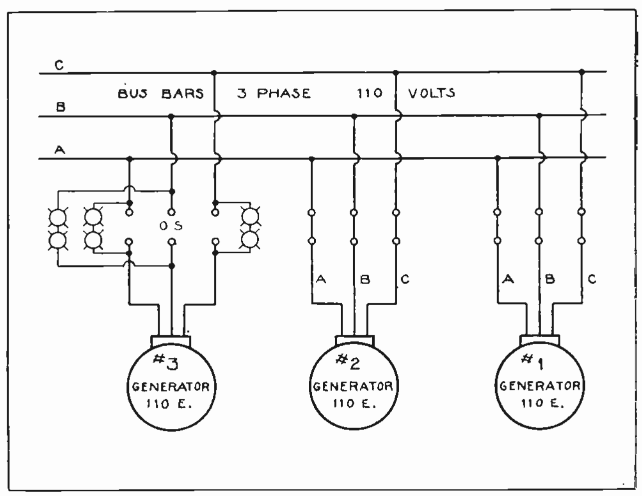

Fig. 93. This diagram shows the method of connecting lamps for phasing out an alternator which is to be operated in parallel with two others.

A sufficient number of lamps must be connected in series in each phase to withstand double the voltage of the alternator. It can readily be seen, therefore, that if the voltage of the machine is higher than 440 volts, it would require a considerable number of lamps in order to use this method, that is if the lamps only were used.

So, with higher voltage machines step-down transformers are often used to reduce the voltage to the lamps. Small power transformers or instrument transformers can be used.

In phasing out a new generator by this method it is necessary to bring it up to its rated speed and voltage. The lamps connected as shown in Fig. 93 will then alternately light up and go dark, due to the generator voltages being out of phase and in phase at different periods.

If all three sets of lamps become bright and dark together or at the same time, it indicates that the proper phases of the new generator are connected to corresponding phases on the opposite side of the oil switch. If the lights do not burn bright and dim together it is then necessary to **interchange or reverse any two leads of the generator which is being phased out.**

While this interchange can be made anywhere between the generator and the oil switch or between the oil switch and the busses, it is usually best to reverse the leads right at the generator terminals. We should never reverse the leads of any other machine to make the phases match with the new generator, as this would reverse the rotation of all of the three-phase motors operating on the system.

Extreme caution should be used never to connect even a small generator in parallel with another one or to live busses, without first carefully phasing it out; because if one A. C. generator is connected in parallel with others when out of phase, it results in practically a short-circuit on the running machines, the same as though one D. C. generator of the wrong polarity were connected in parallel with others.

Care should also be used to see that the lamps are of sufficient number and resistance to stand double the voltage of the alternator, because at certain periods during the alternations they may be subjected to the voltage of the new machine plus that of the running machines, in series.

When phasing out higher voltage machines and using lamps and transformers, the primary and secondary leads of the transformer should be carefully marked and tested if necessary, to determine whether they are of additive or subtractive polarity. These terms will be explained later, in the section on transformers.

Care should also be taken not to reverse either the primary or secondary leads of the transformer, but to have them all connected with the same respective leads both to the alternator and busses.

100. MOTOR METHOD OF PHASING OUT

Fig. 94 shows the connections for phasing out an alternator by means of a three-phase motor. To use this method conveniently and to avoid making mistakes in connections, it is usually best to connect the leads of the three-phase motor in uniform order

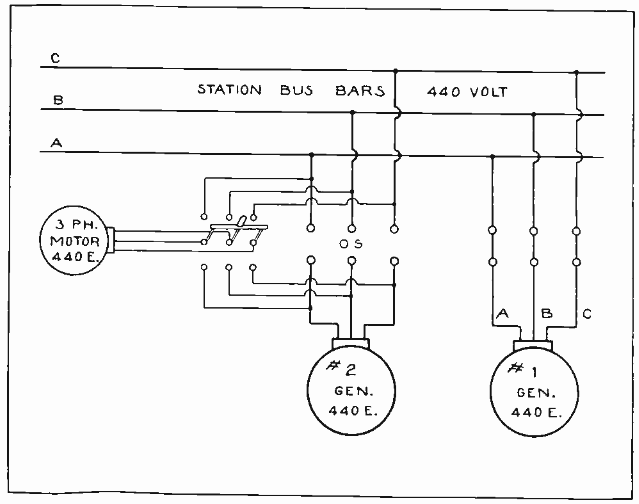

Fig. 94. The above sketch shows the connections and illustrates the method for phasing out an alternator by means of a three-phase motor.

to the blades of a double-throw, three-pole, knife switch.

The outer contacts or clips of the switch on one side are connected to the busses or running generators, while the clips on the other side are connected to the machine which is to be phased out. With this connection the motor can be operated either from the new generator or the running machines. When the connections are properly made, the generator which is to be phased out is brought up to rated speed and voltage. The knife switch is then closed to operate the motor from this generator, and the direction of the motor rotation is carefully noted.

To avoid mistakes, it is best to mark this clockwise or counter-clockwise direction of rotation with a chalked arrow, either on the pulley or the frame of the machine, on the side from which you are observing it. Then open the double-throw switch and allow the motor to come to a full stop. The switch is then closed in the opposite direction, to run the motor from the bus bars and running alternators, and the direction of rotation is again noted.

If the motor rotates in the same direction in both cases, the generators have like phases connected opposite to each other on the switch terminals. If these same leads are carefully connected to the oil switch in the same respective manner, the generators should operate satisfactorily in parallel after having been synchronized.

If the motor rotates in the reverse direction when the switch is in the second position, it will be necessary to **interchange or reverse any two leads of the generator which is being phased out.** The connections should then be tested again by running the motor from each side of the switch, and it should run in the same direction in both positions of the switch blades.

If the voltage of the alternator is too high for any available motor, small power transformers can be used to reduce the voltage for making this test of the phases.

101. SYNCHRONIZING OF ALTERNATORS

As previously mentioned, any A. C. generator must be carefully and accurately synchronized before being connected in parallel with other running generators.

Synchronizing is one of the most critical operations to be performed in a power plant, and should be given careful study in this section of the Reference Set as well as in your department lectures and practice. Be sure to practice this operation thoroughly with the alternators in the A. C. Department of your shop course.

This is one operation which you want to be sure you can perform skillfully and confidently before applying for any position as a power plant operator.

Synchronizing means to bring the generators into step or so that their positive and negative alternations occur at exactly the same time. On large machines this must be accurate to within a few degrees; that is, the same alternations of each machine must have their maximum and zero values occurring at the same instant in each phase.

By referring back to the sine curves which were shown for the voltage alternations in the first A. C. Section of this set, and also by drawing a few curves for yourself, if necessary, you will soon see what is meant by having the alternations occur in phase or in step with each other.

If alternators were connected together when out of phase more than a very few degrees, it would result in very heavy surges of current between the two machines, because of the difference in their voltages at any instant. If two machines were connected together when they were 180° out of phase, this would mean that one generator would be producing positive voltage while the other was producing negative voltage, and it would result in a double voltage short-circuit, the same as though two D. C. generators were connected together with wrong polarity.

The nearer the two machines are to being in phase, the less will be the difference in their instantaneous voltages at any point of the cycle.

By careful adjustment of the speed of the "incoming" alternator, we can by means of a synchronizing device get the two machines exactly in phase with each other. A skillful operator can then close the oil switch at just the right instant and connect the machines in parallel with practically no resulting surge or current flow between the "incoming" and running generators.

If large generators are connected together when they are very much out of phase, it is likely to wreck the machine windings and possibly cause serious damage to the generators and other plant equipment.

The two most common methods for determining when alternators are in synchronism are by the use of either a synchroscope or lamp-bank. A voltmeter is sometimes used for this purpose also. A synchroscope is by far the more reliable and convenient, as it shows whether the incoming generator is running too slowly or too fast and indicates which way the governor or throttle of the prime mover should be adjusted in order to bring this machine to the same frequency as the running machines.

The pointer of the synchroscope also indicates more accurately when the generators are exactly in phase with each other.

The operation and connections of the synchroscope were explained in the section on A. C. Meters, and you should practice synchronizing A. C. generators with a synchroscope as well as the lamp banks in your shop department.

When voltmeters are used, they are connected the same as the lamp bank, which will be explained in the following paragraphs.

Voltmeters to be used for synchronizing should be of the "dead beat" type, or well damped so that their pointers do not oscillate or swing too far beyond the actual voltages. Voltmeters are seldom used for this purpose because of their cost and the fact that a synchroscope, costing very little more, is much more convenient and reliable.

102. SYNCHRONIZING WITH LAMPS

The lamp-bank method of synchronizing is used quite extensively in small plants, where the generators are not large and the cost of the synchroscope is considered prohibitive.

Fig. 95 shows the connections for using lamps to synchronize two alternators. You will note that these connections are practically the same as when lamps are used to phase out an alternator, except that the lamps are arranged with a double-throw, three-pole switch, so they can be used to synchronize either alternator with the busses, according to whichever machine may be running at the time.

The incoming generator, which in this case is No. 1 in the figure, is started and brought up to speed and voltage. The synchronizing switch, S, is then closed to the right and the lamps will alternately become bright and dark, the same as in phasing out an alternator, except that in this case the

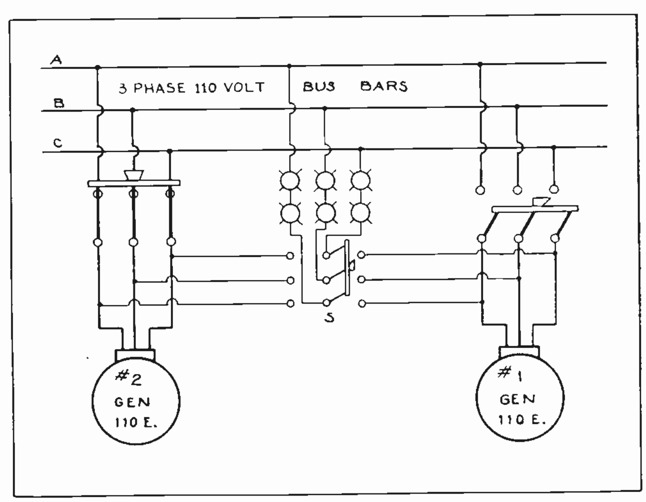

Fig. 95. Connection diagram for synchronizing either of two alternators with the bus bars by means of a lamp bank and double-throw switch.

alternators are presumed to have been phased out and the three sets of lamps should all go bright and dark together.

When the generators are 180° out of phase, or one machine positive and the other negative, their voltages will add together through the lamps and cause the two lamps in series in each phase to burn brightly.

When the generators are exactly in phase—that is, phase A of generator No. 1 reaches its maximum voltage at the same time phase A of generator No. 2 does—these voltages are then opposing each other on the busses and no current will flow through the lamps.

If the frequency of the incoming machine is only slightly different from that of the running machine, the lamps will brighten and darken very slowly; but if the frequency of the incoming machine is considerably different from that of the running machine, the lamps will flicker on and off very rapidly.

So, by adjusting the governor or throttle of the prime mover which drives the incoming generator and watching the operating of the synchronizing lamps, we can tell whether we are approaching the frequency of the running generator or if we are getting farther away from it.

When the speed of the incoming generator is properly adjusted and the frequencies are almost exactly the same, the lamps should go on and off very slowly, actually remaining dark for a second, or two, and requiring several seconds to change from bright to dark each time.

During the middle of this dark period, the switch which connects the incoming generator to the busses should be closed. By watching the speed with which the lamps brighten and go dark throughout several of these periods, one can approximately time the length of the dark period so that the switch can be closed about the middle of this period.

This requires good judgment and skill, which can be obtained only by practice, and you should be sure to obtain this practice on the generators in the A. C. shop department.

One of the disadvantages of using lamps for synchronizing is the fact that an incandescent lamp requires a considerable proportion of its rated voltage to cause the filament to light even enough to be noticeable. Therefore, there may be some small difference in voltage between the two alternators even when the lamps are dark. This is the reason for closing the switch at the middle of the dark period, when the voltage difference between the two machines should be zero.

Alternators should never be paralleled as long as the lamps are burning at all; or, in case a synchroscope is used, as long as it indicates any phase difference between the two machines. If the phase difference is small when the machines are paralleled, they may pull in step; and while there may not be any serious damage the first time this is done, if it is done a number of times the severe shock to the windings will sooner or later damage their insulation or the coil bracing.

The very heavy surges of current which result through the generator windings when they are paralleled slightly out of phase, set up enormous magnetic stresses which tend to distort the conductors at the end of the coils and also apply very heavy pressures against the insulation in the slots. This also results in severe mechanical shock to the entire machine.

103. SYNCHRONIZING WITH SYNCHROSCOPES

The lamp-bank method will probably be encountered in a number of small plants and may often be very handy to you in synchronizing small generators when no synchroscope is available. The synchroscope is, however, by far the most commonly used in modern plants of any size, and because of its extreme accuracy this instrument should be used whenever possible.

Another of the decided advantages of the synchroscope over the lamp-bank is that its pointer indicates whether the incoming generator is running too fast or too slow.

When the synchroscope is used, the governor or throttle of the prime mover is adjusted according to the indication of the synchroscope pointer and whether it is revolving in the direction showing that the incoming generator is running too fast or in the opposite direction showing that it is running too slow.

When the speed of the incoming generator has been adjusted to a point where the synchroscope is revolving very slowly in the "fast" direction the knife switch or oil switch which connects the incoming machine to the busses can then be closed, just as the pointer reaches the mark on the center of the scale.

By connecting the alternators together when the incoming machine is running slightly faster than the running machines, it enables the incoming gen-

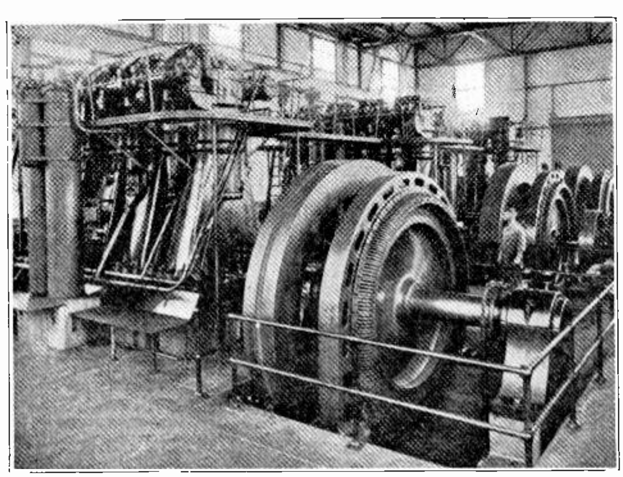

Fig. 95-A. This photo shows a group of alternators driven by Diesel oil engines. Many power plants located in the oil fields, or in places where water and coal are difficult to obtain, are equipped with engines and generators of this type.

erator to pick up its share of the load more readily and smoothly.

When paralleling alternators by means of remote controlled oil switches it is often necessary to allow a fraction of a second for the actual closing of the oil switch. This is done by closing the remote control switch just before the synchroscope pointer reaches the mark on the scale, so that the oil switch will close and parallel the alternators just at the time the pointer is on the mark and the machines are in exact synchronism.

104. STARTING UP ALTERNATORS

The procedure to be followed when starting an alternator and preparing to bring it on to the busses in parallel with others may vary in certain details with the operating policies of different plants, but there are certain general methods and precautions to be followed.

The following material on this subject applies only to alternators which are already installed and in operating condition. The procedure for starting new alternators which are to be operated for the first time will be covered in a later section on the installation and operation of electrical machinery.

When starting an alternator in a small plant, the electrician or switchboard operator may also have to start the prime mover. In large power plants the prime movers are usually started and controlled by the turbine engineers or men of the steam crew.

In either case, a certain amount of time must be allowed for the routine and preparations necessary in starting the prime movers. These points will be covered more fully in a later section on prime movers.

Before starting an alternator we should make sure that the armature and field switches are open. The field switch should be set in the discharge position.

If the exciter is separately driven, it should be started and brought up to full rated speed before the alternator is started. If the exciter is driven from the alternator shaft it will, of course, come up to speed at the same time the main alternator does.

In either case the exciter voltage should be kept low, usually at about 50% of its rated voltage, until after the field circuit to the alternator has been closed. This allows the voltage to be built up more gradually in the armature of the alternator.

The alternator field switch can next be closed, to energize the field poles. Then adjust the exciter voltage until the alternator armature develops its full rated voltage. If the generator is to operate alone and supply power to a line, the armature switch may then be closed. If the generator is to operate in parallel with others, it must first be properly synchronized before closing the armature switch.

In some cases, when starting a single alternator that is to be operated alone, it is desirable to close its armature switch to the line with the alternator voltage at about one-half its full rated value. This allows the generator to pick up any load which may have been left connected to the system, without such heavy current surges through the machine. The voltage can then be brought up to normal by means of the field rheostats, after the armature switch is closed.

Always remember that the three most important requirements before paralleling A. C. generators are: (A) They must be of equal voltage; (B) Generators must have been phased out and have like phases ready to connect together; (C) The generators must be in synchronism.

When these conditions have been obtained the armature switch may be closed and the incoming generator connected in parallel with the bus bars and running machines. The alternators should then operate satisfactorily in parallel, if they are of the proper design and characteristics.

105. ADJUSTING AND TRANSFERRING LOAD ON ALTERNATORS

The next step is to make the alternator which has just been connected pick up its share of the load on the system. This cannot be done by increasing the armature voltage, as is done with direct current generators.

Alternating current generators are caused to take more of the load by slightly increasing the power applied by the prime mover. This is done by adjusting the governor or throttle of the prime mover so it will deliver slightly more power to the alternator.

This, of course, tends to make that alternator on which the power is increased run slightly faster than the others, but the tendency of two or more alternators to hold together in synchronism after they are once paralleled prevents the machine from actually running any faster than the others.

Instead, the additional power applied by the prime mover merely causes this generator armature to advance a few degrees in phase ahead of the others, and this will cause it to pick up its share of the load.

The field rheostat can then be adjusted to reduce any cross currents or wattless currents between the armatures of the alternators in parallel. This is very important, and the field current should be adjusted until the armature current of each alternator is at the minimum for the load they are carrying at that time.

In other words, by having wrong field adjustment on alternators, it is possible to have the sum of the currents from the separate machines equal considerably more than the total load current being taken from the busses. These cross currents between the alternators may result in heating, if they are not kept at a minimum.

When the proper load distribution has been obtained between the generators operating in parallel, they should maintain this division of load, provided the governor of the prime movers is properly adjusted so that all machines respond alike to variations in the load.

106. SHUTTING DOWN AN ALTERNATOR

When the load on a certain power plant or group of alternators is reduced to such an extent that it is not economical to keep all of the alternators operating, one of the machines can be disconnected from the bus and shut down until such time as increased load may again require its operation.

Shutting down an alternator is a simple operation, but there are several important steps to be followed in order to perform this operation properly.

In some small plants A. C. generators are taken off the busses by merely opening their armature switches. This, however, results in a very sudden dropping of the load of the disconnected machine and may result in heavy current surges and fluctuations in the voltage of the other machines.

For this reason many power companies object to this practice, and require that the load be gradually dropped from the machine which is to be disconnected. This can be done in the following manner.

The throttle valve on the prime mover of the generator to be shut down is first closed little by little until the generator drops practically all of its load and the ammeter or wattmeter in its circuit shows its current output to be at a very low value. In up-to-date plants of medium or large size, wattmeters or watthour meters give the most reliable indication when the load is reduced to zero, as an ammeter might still show some flow of wattless current.

This load is, of course, automatically picked up by the other generators, or is in reality simply transferred by reducing the power applied to the alternator which is being shut down.

When by adjustment of field excitation the load on the machine as shown by the ammeter, has been

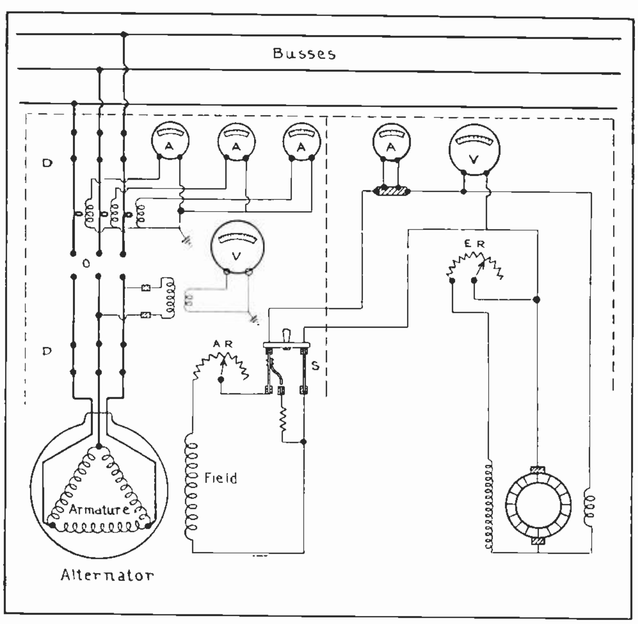

Fig. 96. This diagram shows the wiring and arrangement of a three-phase alternator, and the meters and equipment commonly used on the switchboard panels.

reduced to zero or a very low value, the armature switch is then opened, disconnecting the generator from the busses. The throttle valve of the prime mover is then closed all the way and the generator is allowed to drift to a stop.

After the armature switch has been opened, the field switch may be opened if desired; or the field can be left energized temporarily, in order to bring the generator to a stop in a little shorter time. Brakes are used for this purpose on larger machines. **The field switch should never be opened before the armature switch has been opened.**

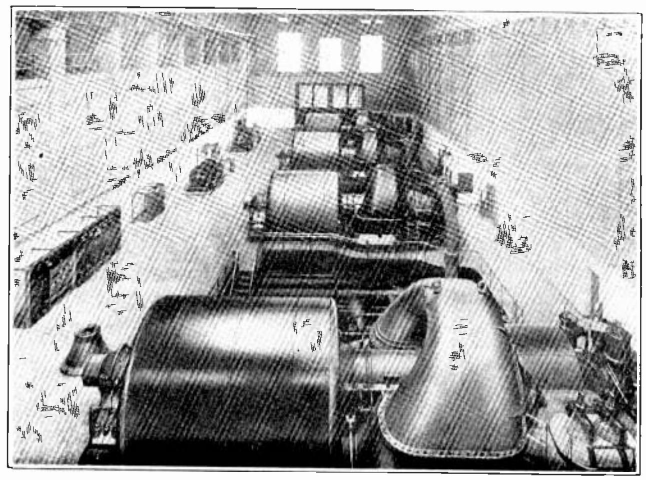

Fig. 97. Interior view of a large power plant showing several of the steam-turbine-driven alternators and also part of the switchboard and the exciter-generators.

When the generator comes to a complete stop and is standing idle, the field switch should always be open. It is also a very good precaution to open any disconnect switches which are between the generator, oil switch, and the bus bars. This will prevent any power flow from the busses to the generator armature if the oil switch should accidentally be closed when the machine is standing idle.

Different generating companies have various special rules to meet the operating conditions in their various plants, and any operator should make a careful study of these rules as well as the general rules and principles which are covered in this section. All such rules are made to provide safety for operators and machines, as well as to provide satisfactory service to the customers to whom the power is supplied.

107. ARRANGEMENT OF INSTRUMENTS AND CONNECTIONS FOR ALTERNATORS

Fig. 96 shows a diagram of the connections for an alternator and its exciter. This diagram also shows the meters to measure the voltage and current of each machine. The three A. C. ammeters are connected, by means of current transformers, to measure the current in each line wire of the alternator.

The A. C. voltmeter is connected by means of a potential transformer to indicate the voltage of the alternator. This voltage, of course, should be the same on all three phases; so it is only necessary to measure it on one phase.

You will note that the voltmeter connections are made between the alternator and the oil switch, O; so that the voltage of the alternator can be read before the oil switch is closed to parallel this machine with any others which may be connected to the busses.

Two disconnecting switches, D, are provided, one on each side of the oil switch. After the oil switch is open and the alternator shut down, these disconnecting switches can be opened with a switch pole, or by hand in the case of low voltage circuits, and thus the oil switch and instrument transformers are separated from the live busses.

This permits any necessary repair work to be done on these devices with safety. The alternator rheostat, A.R., and the field discharge switch, S, are mounted on the alternator panel of the switchboard. The alternator panel is also very often provided with a wattmeter and a watthour meter. The wattmeter is to indicate the power output of the machine at any instant and the watthour meter shows the power in kw. hours which is produced by the machine during any certain time period.

The alternator panels are often provided with switches or plugs for connecting the synchroscope or synchronizing lamps to any machine that is being started. These auxiliary devices are not shown in the diagram in Fig. 96, but they will be covered more fully in a later section on switchboards.

The exciter panel at the right in Fig. 96 contains the D. C. ammeter and voltmeter, for measuring the current to the field of the alternator and the voltage generated by the exciter. The exciter field rheostat, E.R., is also on this panel.

In some power plants the exciter panel is located adjacent to the alternator panels in this manner. In other large plants the direct current from the exciters may be metered and controlled from an entirely separate switchboard.

Among the more important features to be checked and watched in the care of alternators are the following. The temperature of both the windings and bearings should be frequently checked, and the meters watched to see that the machines are not overloaded. The speed and frequency of alternators should be accurately maintained, and the fields properly adjusted to keep cross currents at a minimum between parallel alternators. Tests should be made periodically on the insulation of alternator windings to note any weakness before it results in a complete failure of the machine.

Always see that there is plenty of cool, clean, dry air available for cooling the machines. All parts of the generators should be kept clean, and the windings should be cleaned with compressed air to keep dust or dirt from blocking ventilating passages and causing excessive heating. Additional material will be given on the care of generators in a later section on maintenance of electrical machinery.

Fig. 97 shows the generating room in a large power plant with four large steam-turbine-driven

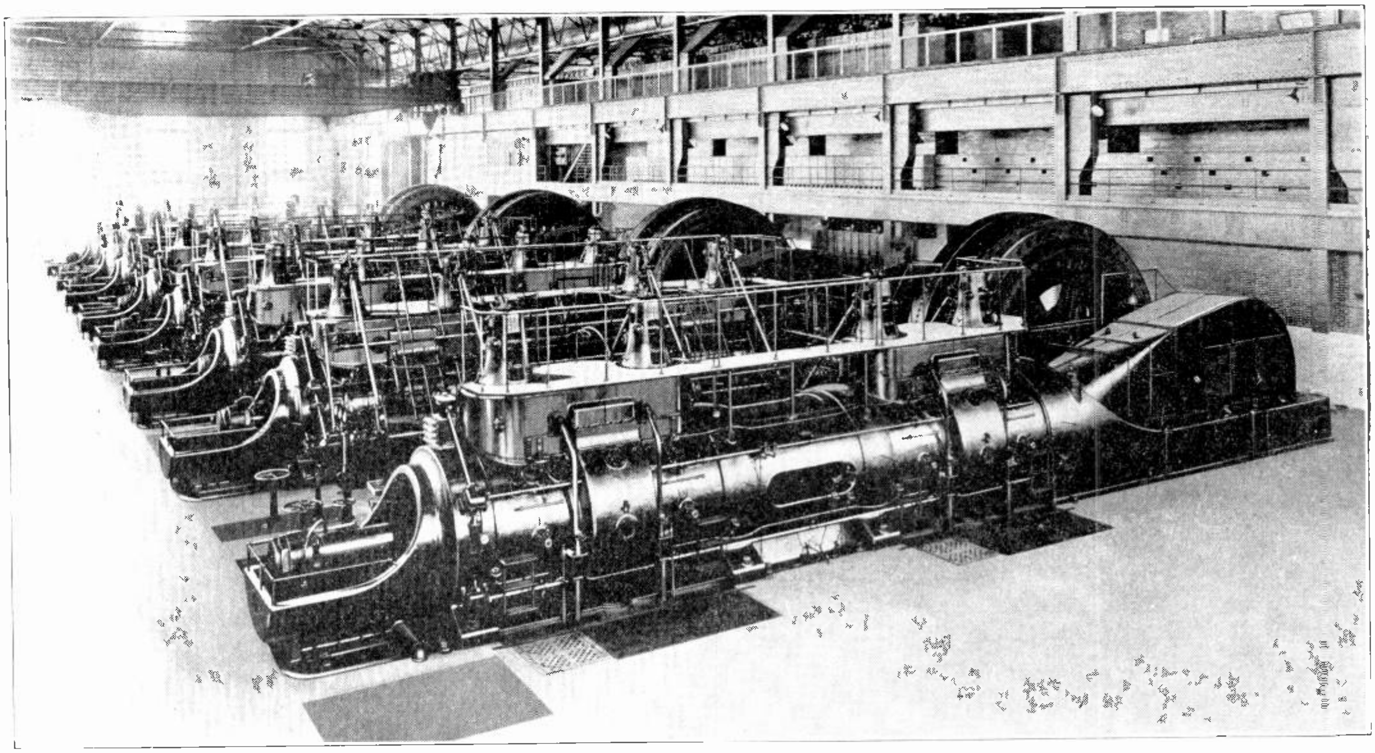

Fig. 98. Privately owned power plant producing alternating current for use in steel mill operations. These alternators are driven by gas engines which burn waste gases as a fuel. (Photo Courtesy Allis Chalmers Mfg. Co.)

alternators which are operated in parallel. Part of the switchboard and also the small exciter generators can be seen at the left of the photo.

Fig. 98 shows a section of a large industrial power plant in a steel mill. Waste gases from blast furnaces are used to operate twin tandem gas engines, and these engines in turn drive the alternators, which are operated in parallel to supply electricity used in the mill.

A great many of the larger factories and industrial plants have their own private power plants to generate the vast amount of electrical energy which they use.

Operation of electrical equipment in plants of this type as well as in the mammoth generating stations which are owned and operated by public utility companies, provides fascinating and profitable work for many thousands of trained men.

To be able to qualify for a responsible position in a plant of this kind is well worth a thorough study of everything covered in this entire Reference Set and in your shop course.

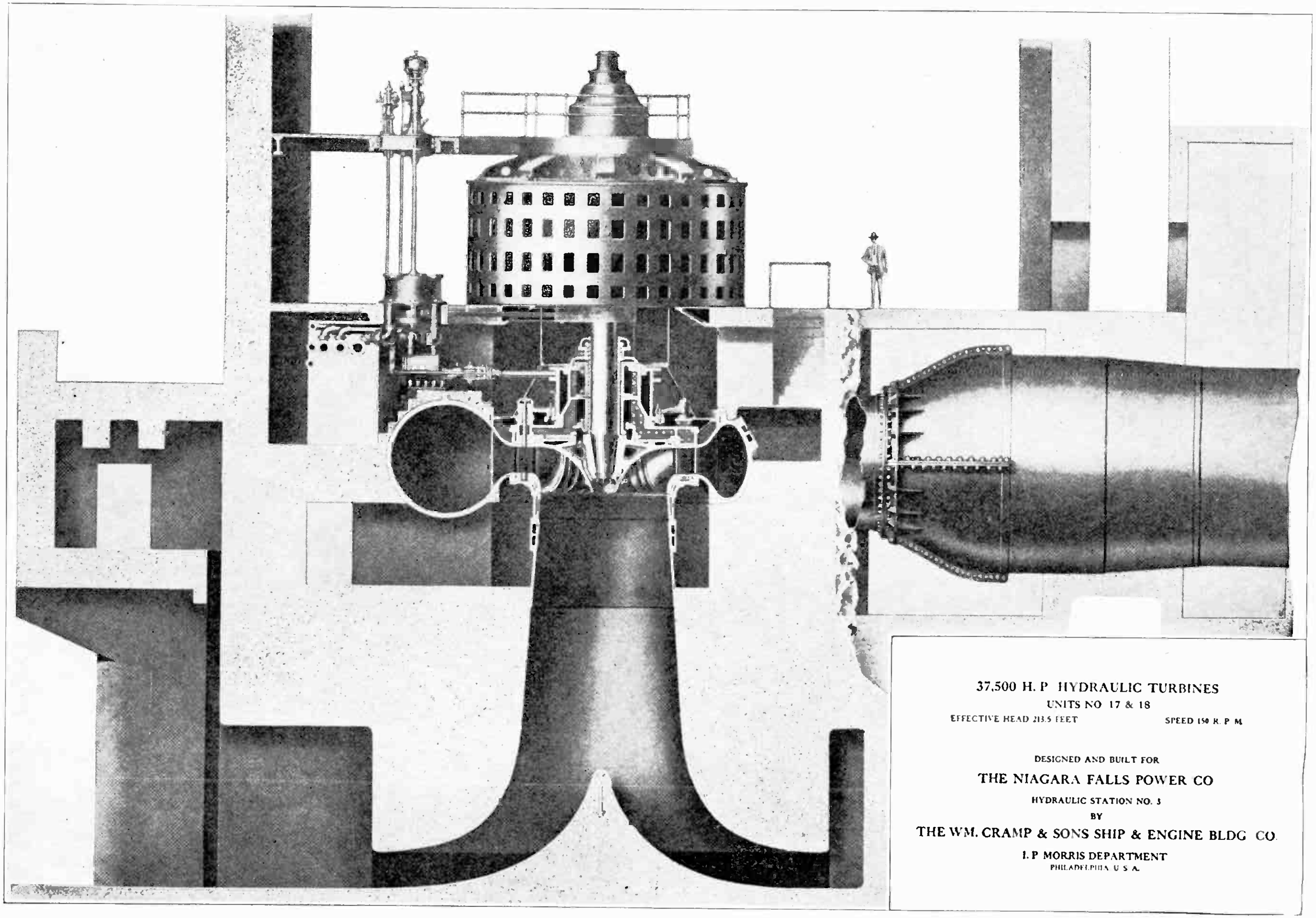

Fig. 98-A. This photo shows a large water-wheel driven alternator and also an excellent sectional view of the hydraulic turbine which drives the alternator. Note the size of the generator compared with the man in the picture. Hundreds of machines of this type are in use in hydro-electric power plants throughout the country.

COYNE Electrical School

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ESTABLISHED 1899

ALTERNATING CURRENT

AND

A. C. POWER MACHINERY

Section Four

Transformers

Construction Features

Methods of Cooling

Operating Principles

Ratios, Voltages, Polarities

Connections

Star and Delta, Paralleling, Phasing Out

Polarity Tests, Grounding

Special Transformers

Tap Changing, Scott, Auto Transformers

Induction Regulators, Instrument Transformers

Tests, Field Problems, Maintenance

TRANSFORMERS

We have already mentioned that it is necessary to use high voltage in order to transmit large amounts of electrical power economically over long distance lines. This, you will recall, is one of the principal advantages mentioned for alternating current, because it is possible to economically increase the voltage of alternating current with transformers.

A transformer is a device by means of which alternating voltages may be stepped up or down as desired. When the voltage of a circuit is raised or lowered by means of a transformer, the current capacity is usually varied in the opposite direction by the same proportion.

If we raise the voltage the current is reduced, or if we decrease the voltage the current is increased. For example, if we consider a circuit having 5,000 watts at 100 volts, the current in this case will be W ÷ E, or 5000 ÷ 100, which equals 50 amperes.

If we were to raise the voltage of this same circuit to 1000 volts the current necessary to develop the same power would then be 5000 ÷ 1000, or 5 amperes.

It is easy to see that a much smaller conductor could be used to carry the 5 amperes than would be needed for 50 amperes, so the same amount of power can be transmitted over smaller wires when higher voltage is used. This is the principle applied to modern transmission lines, and whenever a large amount of power is to be transmitted to some distant location the voltage is stepped up by means of transformers to some one of the standard high voltages, and the necessary current is thereby reduced a corresponding amount.

It is then possible to use a much smaller amount of copper in the conductors, and yet operate the transmission lines at a certain economical percentage of loss. These smaller conductors require much lighter supporting structures, such as the poles and steel towers, and lighter insulators and fittings.

As the cost of the copper in a transmission line is very great and the poles or towers also represent a large investment, the saving effected by the use of higher voltage is enormous.

For example, 50,000 kw. can be transmitted many miles at a potential of 100,000 volts over a copper conductor less than an inch in diameter, but if this same amount of energy were to be transmitted at 500 volts, it would require a conductor over a foot in diameter to carry the current with the same amount of loss.

From these points just mentioned, it is evident that alternating current provides a very convenient and economical means of transmitting large amounts of power for considerable distances, by stepping up the voltage at the generating plant with transformers and then stepping it down again to safe and suitable voltages for the equipment at the point where the energy is to be used.

By far the greater amount of electrical energy is used at voltages from 110 to 440. Some of the larger motors, however, are operated at voltages from 2300 to 6600, and in some cases as high as 12,000 volts or more.

Transformers are one of the most efficient pieces of electrical equipment that we have; the efficiencies of some of the very largest sizes ranging over 99%. These high efficiencies are obtainable because the transformer has no moving or wearing parts and therefore no friction or mechanical losses.

For this same reason, transformers require very little care and attention, except to maintain the proper insulation and cooling of their windings.

Power transformers are often referred to as **static transformers**, even though they have nothing to do with static electricity. This term is used because their parts are all stationary. We mention this term at this point because it is often confusing to the student or electrician to hear a transformer called by this term, if he doesn't know what it means.

108. TYPES OF TRANSFORMERS

We have already learned that a transformer consists primarily of an iron core which provides a path for the magnetic flux and on which are placed the two windings: one called the **high tension winding** and the other the **low tension winding.** The high tension winding (H.T.) is the one which has the greatest number of turns, and the low tension winding (L.T.) is the one which has the smaller number of turns.

These windings are also commonly referred to as **primary** and **secondary** windings. The primary winding is always the one which is connected to the source of power. The secondary winding is always the one which receivers its power from the primary by induction, and is the one connected to the load.

There are several common types of transformers and they are classified according to the manner of their core construction. These are known as: the **core** type, **shell** type, and **distributed** type.

It may help you to distinguish between these types by remembering the number of magnetic paths or circuits which each type of core provides for its flux. The simple core type provides one path; the shell type, two paths; and the distributed type, three or four paths.

The sketches in Figs. 99 and 100 show the differences between these common types of transformer cores. Fig. 99 shows the plain core-type transformer, consisting of four sides, or legs as they are commonly called, arranged in the form of a square or rectangle. The primary and secondary coils can be wound on opposite legs, as shown in this figure, or they can both be wound on the same core leg if desired.

When the primary winding is excited with alternating current, it sets up an alternating magnetic flux which is carried by the core over to the secondary winding. As the lines of force expand and contract, due to the alternations of the current, they cut across the turns of the secondary winding, thereby inducing voltage in this winding by the principles of electro-magnetic induction which were explained in the Elementary Section of this reference set.

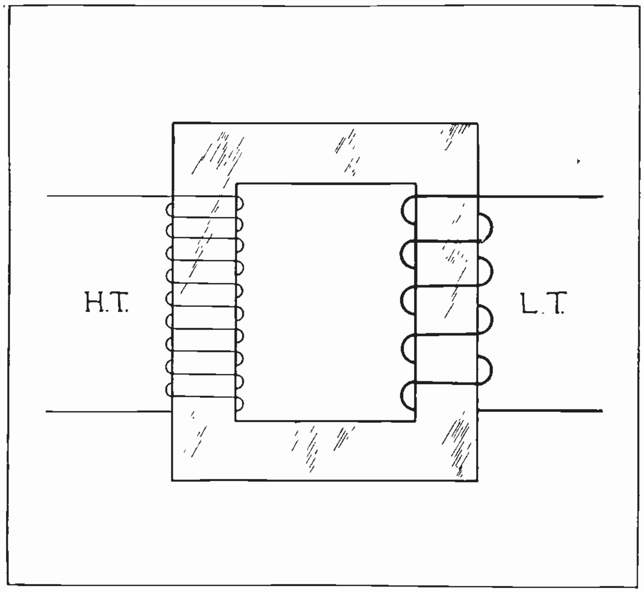

Fig. 99. This sketch shows the core and windings of a simple transformer. The winding on the left with the greater number of turns is the high tension winding, and the one on the right the low tension winding.

The amount of voltage which will be induced in the secondary winding depends upon the ratio of the number of turns in the primary and secondary coils. If the secondary has fewer turns than the primary, the voltage will be stepped down; on the other hand, if the secondary has a greater number of turns, the voltage will be stepped up.

An ordinary transformer can be used to step the voltage either up or down, depending upon which of the windings is made the primary, or excited by the applied voltage. So we find that, in the case of step-up transformers, the primary is the winding with the fewer turns; while on a step-down transformer, the primary is the winding with the greatest number of turns.

109. TRANSFORMER CONSTRUCTION

The purpose of the transformer core is to provide a low reluctance path for the magnetic flux. Transformer cores are therefore made of a special grade of soft iron or silicon steel, and are built up of thin laminations. These laminations are insulated from each other, either by a coating of insulating varnish or by an oxide scale which is formed on their surfaces by a heat-treating process.

This laminated construction reduces eddy currents which would otherwise be set up by the alternating flux and would cause the core to overheat.

The left view in Fig. 100 shows a sketch of a shell type transformer core with the primary and secondary windings both placed on the center leg. On the right in Fig. 100 is shown a sketch of the distributed type core on which the coils are also wound on the center leg and are surrounded by the four outside legs of the core.

This distributed-type core is used principally for low-voltage lighting and distribution transformers in sizes under 50 kv-a. The large area of core iron, well distributed around the coils, makes the "no load" losses very low with this type of transformer, so that it is ideal for use on lighting circuits where the load may be very small at times.

The core-type and shell-type transformers are both suitable for large capacity and high voltage work. The core-type is best suited for the very high voltages, because its coils can be more easily wound and insulated than those of the shell-type. The windings of the core-type transformer, being located more on the outside of the core, can therefore radiate heat away from the windings more rapidly.

The shell-type core, because of its shape and the location of the windings on the center leg, provides somewhat better mechanical protection for the coils during handling in and out of the transformer case. The shell-type transformer is best suited for moderate voltages and heavy currents.

Fig. 101 shows a complete distributed-type, transformer core of the three-leg construction. This view shows the manner in which the core legs are assembled from the thin laminations and also the

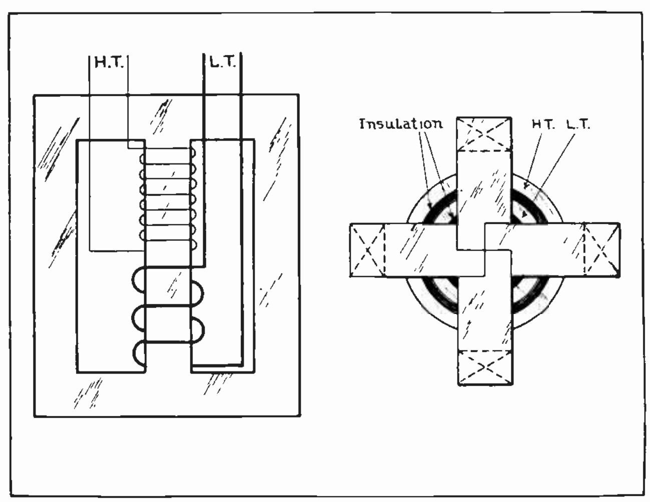

Fig. 100. The diagram on the left shows a transformer with a shell-type core, and on the right is shown the top view of a transformer with a distributed-type core. This view shows the top edges of the coils and insulation, while the sketch on the left shows a schematic diagram of the coils in their position on the core.

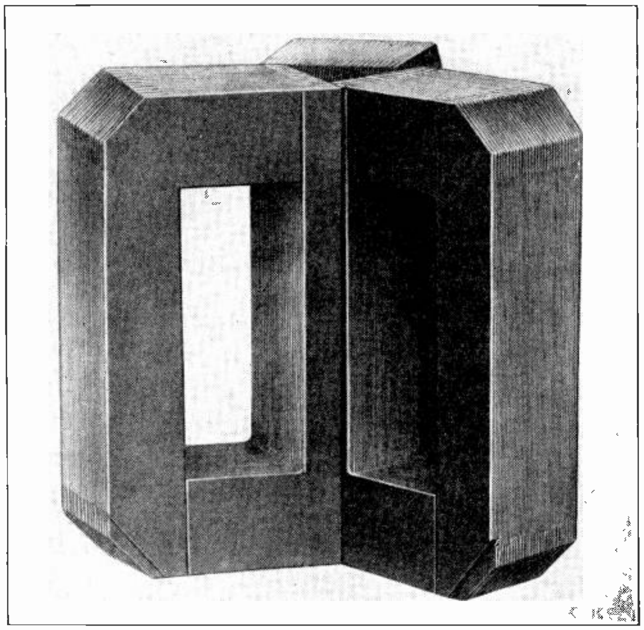

Fig. 101. The above photo shows a complete core of the three-sided type for a distributed core transformer. (Photo courtesy General Electric Co.)

manner in which the laminations are overlapped at the corners of the core, in order to provide a good magnetic path of low reluctance.

110. TRANSFORMER WINDINGS

Transformer coils are wound with insulated copper wire, some of the smaller sizes being wound with round wire, while square or rectangular wire is used for practically all of the medium and larger sized units.

The square and rectangular wires form a more compact and solidly built coil and also provide better conductivity for the heat to flow out of the windings. The coils are usually built up in a number of carefully wound layers and each layer is well insulated from the preceding and following ones.

It is only in a few types of very small transformers that the coils are wound directly on the core legs. In practically all medium-sized and larger transformers the coils are form-wound and then slipped over the legs of the transformer core before the core is completely assembled.

The coils, after being wound, are thoroughly dried by being heated in ovens and are then dipped in hot insulating compound to thoroughly insulate every turn from the adjoining turns.

In many cases the dipping or impregnating process is performed in air-tight tanks, so that the coil can first be subjected to a high vacuum to draw out every bit of moisture and air from the windings. The hot insulating compound is then applied under pressure to force it into every crevice and space in the turns of the winding.

The coils are then thoroughly baked to dry out and harden the insulating compound so it will present a smooth, hard surface and prevent moisture, dust, and dirt from getting into the windings during operation of the transformer.

After the coils are thoroughly insulated and baked, they are placed upon the well-insulated legs of the iron core. The core insulation consists of several layers of fiber or fish paper; or, in some cases on the higher voltage units, it consists of a special bakelite or composition tube.

Fig. 102 shows the partly assembled core for a distributed-type transformer, and the primary and secondary coils ready to be set in place over the center leg of this core as soon as it is insulated. The primary coil, shown in the center of this figure, is built up of several layers which have been form-wound and then thoroughly insulated by a wrapping of tape. The secondary winding, shown on the right, is built up of a number of separate coils, each of which is well insulated from the others.

These coils are then connected in series to form a complete high-voltage winding. This type of construction provides better separation and insulation of the sections of the secondary winding, between which very high voltages exist.

A heavy layer or tube of high-grade insulation is also placed between the low tension and high tension windings to prevent a flash-over from the high-voltage winding to the low-voltage coil.

After the L.T. and H.T. coils are in place on the core, they are securely wedged and anchored, to prevent any possible moving or distortion due to heavy magnetic stresses set up around the coils when the transformer is loaded, or during the possible occurrence of short-circuits.

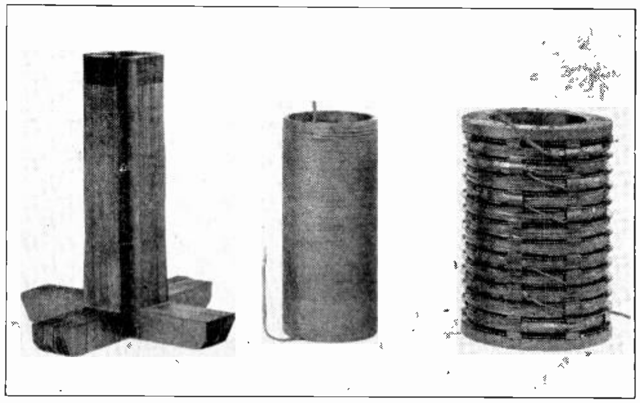

Fig. 102. This view shows a partly assembled core of the distributed type and the primary and secondary windings which are ready to be placed on the core. (Photo courtesy General Electric Co.)

Fastening the coils securely in place also prevents them from rubbing against the core and having their insulation damaged by the slight vibration which is set up by the alternating fluxes in the core laminations.

Fig. 103 shows a completed transformer element with the windings in place on the core, the laminations of the outer and top sides of the core having been assembled after the windings were placed on the center leg. The whole core is then securely clamped by means of bolts to prevent excessive vibration of the laminations.

If these laminations are not clamped tightly together, the reversing magnetic fluxes will cause them to vibrate excessively and create a great deal of noise during the operation of the transformer. Loose laminations might also chafe the insulation of the windings.

In Fig. 103 you may also note the manner in which the leads are connected to the coils and brought up to a terminal plate of porcelain or insulating material. The heavy, stiff, copper leads are then carried on up to the point where they leave the tank or transformer case.

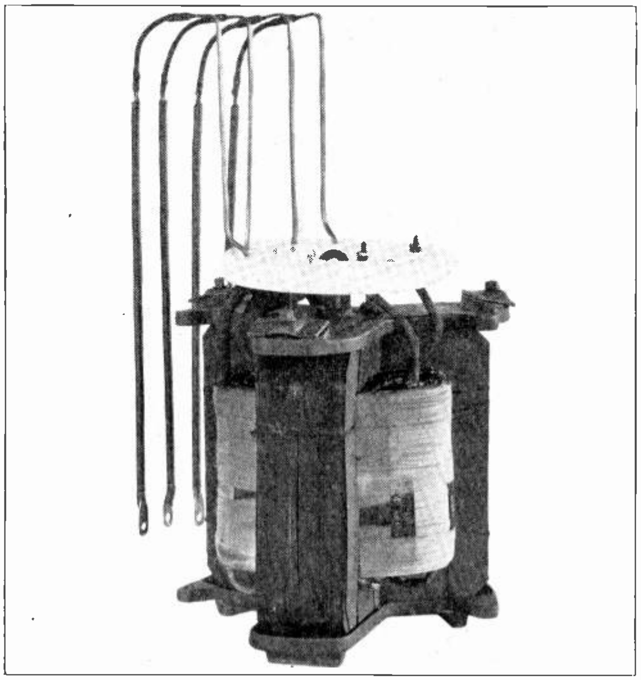

Fig. 103. Complete transformer core and windings. Note how the legs of the core are assembled to form complete magnetic paths around the coils. (Photo courtesy General Electric Co.)

Fig. 104 shows another transformer winding, consisting of form-wound coils assembled in several layers. These layers are separated or spaced from each other by strips of wood, the ends of which can be seen around the left end of the winding. This type of construction not only insulates the sections of the coil from each other, but also provides spaces for the circulation of the cooling air or oil to carry away the heat from the inside of the winding more easily.

A winding built up of a number of separate layers or sections in this manner may have these sections connected either in series or parallel, according to the voltage and current capacity desired from the transformer.

111. SINGLE-PHASE AND POLYPHASE TRANSFORMERS

The transformers we have so far considered and shown in the figures have been of the single-phase type. Transformers are also made in polyphase types, as shown in Fig. 105. This photo shows a complete three-phase transformer element with the primary and secondary windings of each phase located on a separate leg of the core.

From this it is easy to see that a three-phase transformer is simply a combination of three single-phase transformers all assembled on one core. The low voltage windings of the transformer shown in Fig. 105 are inside the high voltage coils and next to the core legs. The high voltage coils which are placed over the others can be clearly seen in this view. Note carefully the manner in which the separate sections of the coil are insulated from each other, and also the insulating barriers placed between the three coils to prevent a flash-over from one winding to the next. The leads for connecting the coils to the line are shown carefully taped and marked, and brought up to separate insulating supports above the core.

A three-phase transformer requires less core material than three single-phase transformers of the same capacity. This is due to the fact that in the three-phase transformer the magnetic fluxes of each phase use the same core at alternate periods as the alternations and fluxes of each phase occur 120° apart. Therefore, the advantages of polyphase transformers are: that they require less core material; are lighter in weight; and occupy less floor space in a power plant or substation than three single-phase transformers of the same capacity.

One of the disadvantages of a polyphase transformer is that, in case of trouble or breakdown in the insulation or windings, all three phases must be cut out of service for repairs; while, in the case of single-phase transformers, the one defective unit can be disconnected for repairs, and service can be maintained to the customers either by substituting another single-phase unit or by a special open-delta

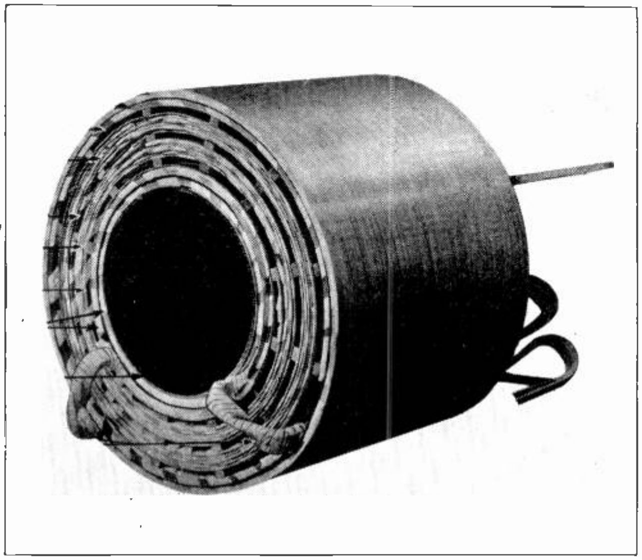

Fig. 104. This view shows a transformer winding which is built up in layers that are spaced apart with wood strips to allow circulation of cooling oil through the winding. (Photo courtesy General Electric Co.)

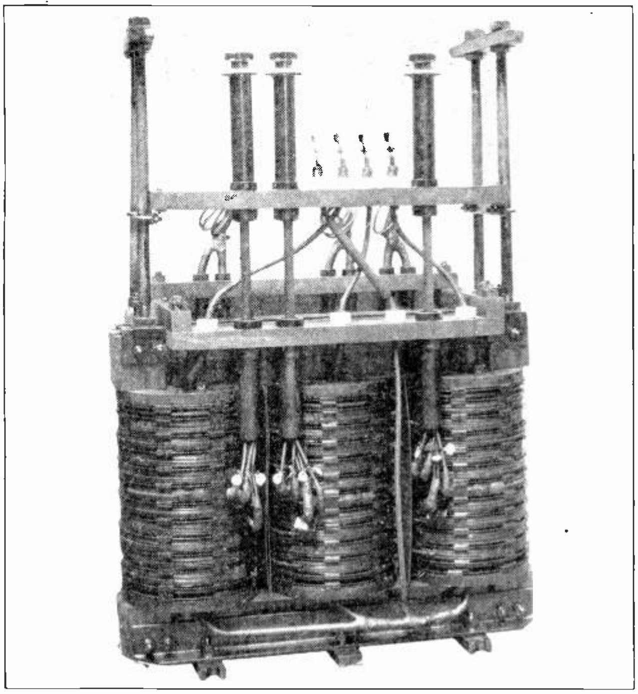

Fig. 105. Complete three-phase transformer core and windings ready to be placed in the tank and covered with oil. (Photo courtesy General Electric Co.)

connection to the remaining two units. This connection will be explained in later paragraphs.

In modern transformers, however, the construction and insulation of the coils is such that under ordinary operating conditions there is very little chance of breakdown or failures.

112. TRANSFORMER LOSSES

Although transformers are very efficient devices, they have certain small losses which take place within their windings and cores during operation. These losses are commonly referred to as **copper losses** and **core losses.**

The copper loss is due to resistance of the coils, which causes a certain amount of the energy to be transformed into heat within the windings. This loss is proportional to the square of the current in the windings, and is therefore approximately zero at no load and maximum at full load.

The core loss consists of eddy current losses and hysteresis losses which are set up in the core by the reversing magnetic flux. Eddy currents, you will recall, are low-voltage short-circuited currents which are caused to flow in various areas of the core by the magnetic lines of force cutting across the core in varying intensities. These eddy currents are reduced and kept at a minimum by the laminated construction of the core; but the small amount which still exists, even in the best core construction, will cause a certain amount of heat to be developed in the iron.

Hysteresis loss is due to the reversal of the magnetic charges of the molecules of the iron as the alternating flux constantly reverses in the core. This loss also tends to produce a certain amount of heat in the core.

The core losses remain approximately the same at no load or full load of the transformer, because they are always proportional to the magnetizing current and flux.

These losses and tests to measure them will be more fully discussed in later paragraphs of this section.

113. TRANSFORMER COOLING

In a transformer which is operating under full load, a considerable amount of heat is produced by the copper and core losses. This heat must be removed and carried away from the windings and core, because if it were confined and stored up within them it would soon cause the temperature to rise so high that it would burn or damage the insulation of the windings.

Transformers must also be kept cool to maintain their high operating efficiency, because the resistance of the copper in the windings increases with the temperature increase and thereby increases the I^2R loss.

In very small transformers, such as bell-ringing and toy transformers, instrument transformers, etc., the heat is carried away by the natural circulation of air around the core and windings.

On larger power transformers some additional means of cooling the windings must be provided. Transformers are often classified according to their methods of cooling, as follows: **natural air cooled, forced air-blast cooled, oil cooled,** and **oil and water cooled.**

Natural air cooling is used only in the smaller types, as previously explained.

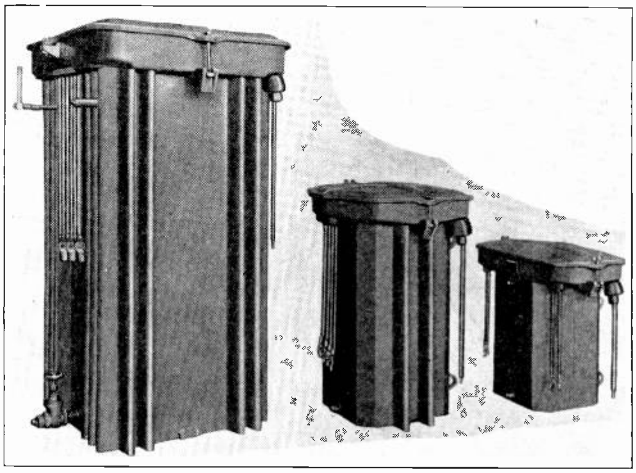

Fig. 106. This view shows three different sizes of common power transformers. Note the cooling flanges or ribs in the tanks of the two larger ones. (Photo Courtesy General Electric Co.)

114. AIR-BLAST COOLING OF TRANSFORMERS

Transformers that are cooled by forced air circulation have their core and windings enclosed in an iron case or jacket which is open at the bottom and top. Clean, dry air under low pressure is forced upward through the windings and, in this manner, carries away the heat much more rapidly than natural air-circulation would.

The air for cooling transformers of this type is supplied by motor-driven fans and is usually fed to the transformers through an air passage or chamber which runs under the floor on which the transformers are located.

Air passes up through the transformers and exhausts, into the room in which they are located, escaping through open windows or air-vents in the building.

Quite often a small ribbon or cord is attached to the top of the transformer casing, directly in the exhaust air opening, so that it will be blown upward and kept fluttering in the air. This provides an indication of failure of the air supply.

It is very important that the air be kept circulating at the proper rate through transformers of this type or otherwise they would quickly overheat.

The air intake for supplying fresh air to air-blast transformers should be located where it will not draw any moisture or dust, as either of these would quickly deteriorate the insulation on the transformer windings, and dust would tend to clog the air passages between and around the coils.

Very often a cloth screen is placed over the air intake to stop the passage of fine dust and a certain amount of moisture.

115. OIL-COOLED TRANSFORMERS

The common oil-cooled transformers of the small and medium sizes have their cores and windings

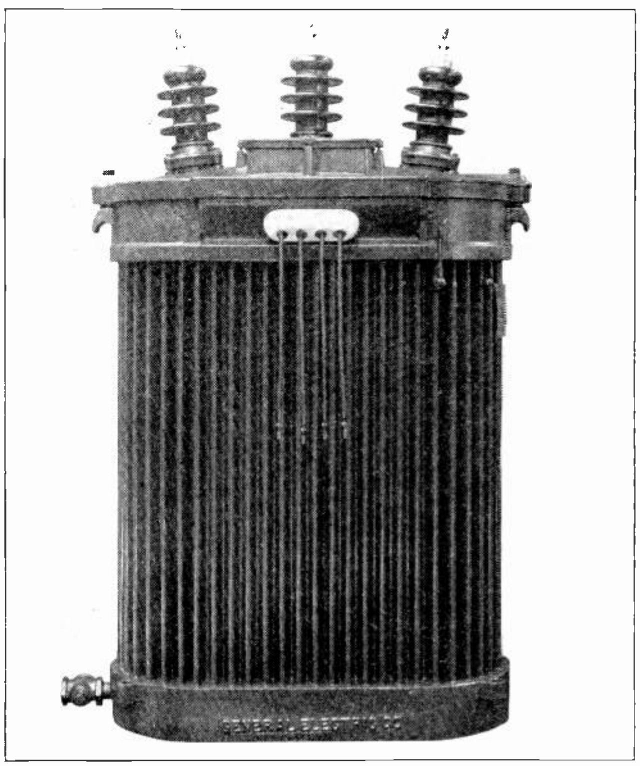

Fig. 107. Three-phase power transformer for high voltage operation. Note the large insulating bushings and also note the manner in which the entire tank is corrugated to provide a greater heat-radiating surface.

immersed in a tank of insulating oil. This is by far the most common type of transformer in use.

The oil, which is of a special grade known as transformer oil, not only serves as a cooling agent for the windings and core, but also serves as an excellent insulation between the layers of the winding and the core.

This oil flows into all crevices and passages between the windings and conducts the heat through the liquid to the metal tank, from which it is given off to the outside air.

Fig. 106 shows several transformers of the oil-cooled type, the capacities of which, from left to right, are: 150 kv-a., 37½ kv-a., and 15 kv-a. The tanks of these transformers are made of either cast iron or pressed steel. The pressed steel tanks are much lighter in weight and more durable mechanically; because, if they are dropped or bumped, it will usually only dent the tank instead of cracking it, as often occurs with cast iron.

On the small sizes of transformers, the tanks usually have a plain, flat surface on each side, as shown on the 15 kv-a. unit at the right in Fig. 106. On the larger sizes, the sides of the tank are usually corrugated or provided with projecting fins as shown on the two larger transformers in this figure. This construction greatly increases the area or surface of the metal which is in contact with the air, and thus enables the air to absorb and carry away the heat from the tank much more rapidly.

Note the manner in which the coil leads are brought out of the transformer case through insulating bushings, which are usually made of porcelain. The cases are equipped with covers which can be removed for inspection of the windings or for changing the connections at the terminals inside. These covers are provided with a washer or gasket around their edges so that, when they are clamped securely in place by the bolts and nuts shown in the figure, they seal the transformer tightly and keep out practically all dirt and moisture.

Transformers of this type and smaller, ranging down to 1 kw. in size, are the types commonly seen on poles throughout the cities and in many rural districts. They are used to step the voltages of the transmission or distribution lines down to that used in homes for lighting or in shops for power purposes.

Fig. 107 shows a complete three-phase transformer which has the entire surface of the case deeply corrugated to provide sufficient cooling area. The high-tension winding of this transformer is constructed for 25,000 volts, and you will note the much larger insulating bushings through which the high-voltage leads are brought out at the top of the case.

You will note also that the transformer cases shown in these figures are provided with drain plugs or valves at the bottom, so that the oil can be drained out and replaced whenever it becomes dirty or has absorbed too much moisture.

During operation throughout a period of several months or longer the oil will often absorb a little moisture, and the presence of even very slight amounts of water in the oil greatly reduces its insulating qualities. It is therefore necessary at times to replace or dry out this oil. This will be more fully covered later under Care and Maintenance of Transformers.

116. COOLING TUBES OR RADIATORS

On very large power transformers, ranging from 300 kv-a. to 10,000 kv-a. and up, the cases are usually provided with a number of pipes or tubes on the outside, as shown in Fig. 108. Some smaller transformers are equipped with these cooling tubes, if they are to be located in places where it is difficult to cool them otherwise. These tubes connect to the top and bottom of the tank and allow the oil to circulate through them from top to bottom, by the natural movement of the oil caused by its being heated inside the transformer and cooled in the tubes.

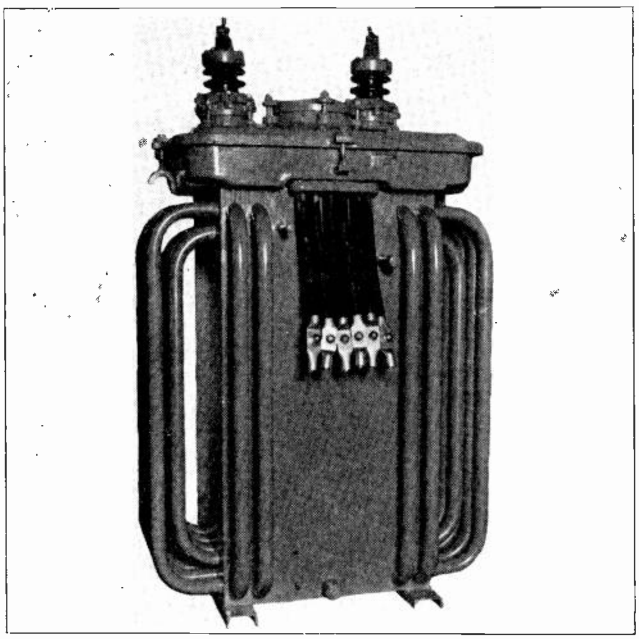

Fig 108. This transformer is equipped with cooling tubes to allow the oil to circulate outside of the tank and give off its heat more rapidly to air.

The heated oil around the transformer coil and windings tends to rise to the top and pass out of the tank into the top ends of the tubes. In the tubes it is cooled off more rapidly, as they are completely surrounded by air, and the oil is thus caused to flow to the bottom of the tubes and back into the transformer.

The oil is kept continually circulating in this manner by the thermo-siphon principle just explained.

Fig. 109 shows a bank of three large single-phase power transformers, each of which has a capacity of 30,000 kv-a. These transformers have a high-voltage winding which produces 220,000 volts. Note the very large insulating bushings through which the high voltage leads are taken out to the line.

These transformers are equipped with groups or sets of cooling fins or tubes which are commonly called radiators and are clearly shown in this photo. These sets of cooling fins are adjustable to take advantage of spacing of the transformers and the air currents around them. They are also removable for cleaning.

The cooling of this type of transformer is sometimes further improved by directing a blast of air against these cooling fins by means of motor-driven fans and sheet metal tubes to direct the air through the cooling fins.

117. OIL AND WATER COOLED TRANSFORMERS

In some cases, where it is difficult to sufficiently cool transformers by means of natural oil circulation through cooling tubes, oil and water cooled transformers are used. In transformers of this type a coil of copper tubing or pipe is located in the oil, above the core and windings.

Cold water is circulated from the outside through this copper piping and rapidly absorbs the heat from the top level of the oil, which is always the hottest in any transformer. Fig. 110 shows a transformer equipped with a cooling coil of this type.

The heat passes easily through the copper tubing because copper, as you will recall, is a good conductor of heat. The heat is thus absorbed by the water and continually carried away by the new supply of cool water which is circulated constantly through the cooling coil, by a pump or by a connection to a local water supply system.

118. AUXILIARY OIL TANKS AND BREATHER PORTS

In Fig. 109 you will note a special oil tank or reservoir mounted on top of each of the transformers. This tank, which is commonly called an oil conservator, is used to maintain the oil level above the top of the main tank and thereby keep the transformer tank completely filled with oil and exclude all air from it.

The smaller outside tank, which is only partly filled with oil, provides the necesary air space to allow for expansion of the oil in the main tank with increased temperature during increases of load. This type of construction also exposes a much smaller area of the top surface of the oil to the air, and thereby reduces the amount of moisture that the oil will absorb in a given time.

In some cases the transformers are provided with a breather port or opening which allows the air to pass in or out of the tank, during expansion and contraction of the oil with temperature changes. This breather can be equipped with a filter of calcium chloride through which the air must pass.

Calcium chloride has a great affinity or attraction for water and therefore absorbs practically all mois-

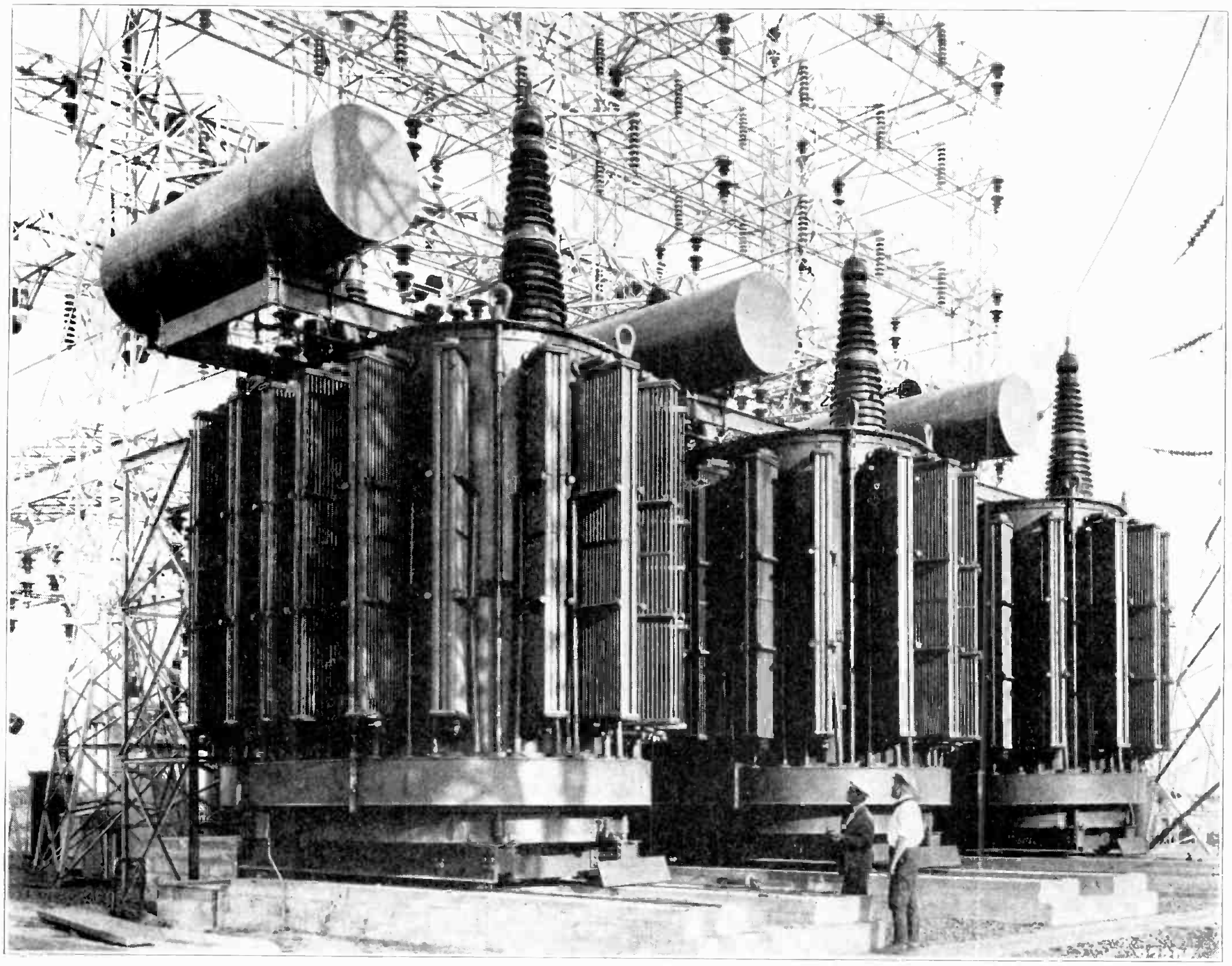

Fig. 109. This photo shows a bank of large power transformers in the foreground and the structure of a high voltage switching station in the background. Note the cooling radiators on the sides of the transformer tanks and also the large insulating bushings which are used for the 220,000-volt leads. Transformers of this type are used in connection with high voltage transmission lines to step the voltage up or down at the sending or receiving ends of the line. (Photo courtesy General Electric Co.)

ture from the air before it is allowed to enter the transformer.

119. TRANSFORMER OPERATING TEMPERATURES

Transformers are commonly designed to withstand temperature increases of 55° C. to 75° C. above normal temperature. This variation in maximum operating temperatures is due to the different classes of insulation which are used.

Transformer windings which are insulated with impregnated cotton, silk, and paper cannot be operated at such high temperatures as those which are insulated with mica and other special insulating compositions.

Practically all large transformers are provided with thermometers which indicate the operating temperatures at all times. When operating or caring for transformers which use forced air or circulating water in their cooling, **it is very important to regulate the air and water so that the maximum temperatures for which the unit is designed will not be exceeded.**

It is also well to remember always that the temperature ratings of electrical machinery are commonly given in the centigrade scale.

When we say that a transformer is allowed to operate at 55 degrees centigrade above normal temperature, its temperature is considerably higher than 55 degrees Fahrenheit. The centigrade scale has its zero point at 32 degrees on the Fahrenheit scale, and its 100-degree point is at 212 degrees Fahrenheit. One degree of the Fahrenheit scale is equal to only 5/9 of a degree centigrade.

So, to determine the value in degrees F. of any certain temperature above freezing, which is expressed in degrees C., we can use the following formula, or rule:

$$\text{Temp. F.} = (\text{C}° \times \frac{9}{5}) + 32$$

Or, to determine the C. temperature of a certain F. value, we can use the formula:

$$\text{Temp. C.} = (\text{F}° - 32) \times \frac{5}{9}$$

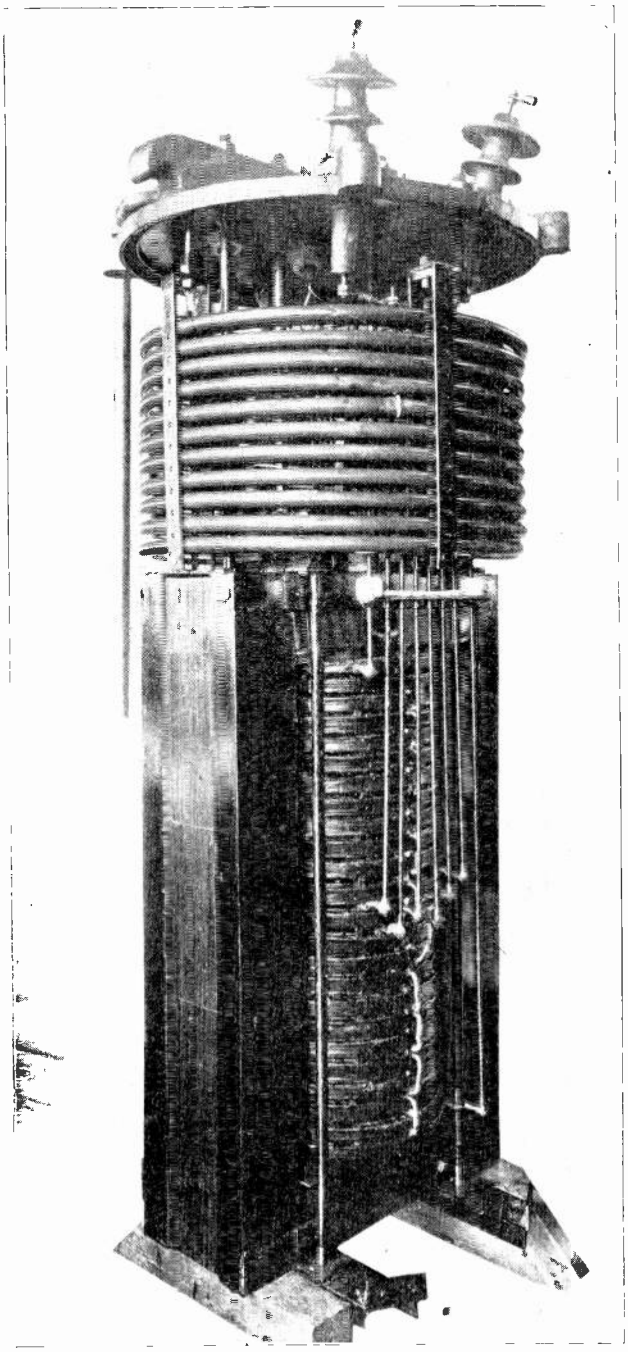

Fig. 110. This view shows a single-phase power transformer equipped with a coil of copper tubing through which water is circulated to cool the transformer and the oil which surrounds it.

Fig. 111 gives a convenient table of comparative temperature values in both the centigrade and Fahrenheit scales. From the table we can quickly find that 55° C. is equal to 131° F., and 75° C. is equal to 167° F., etc.

120. SPECIAL TEMPERATURE AND LOAD INDICATOR DEVICE

For small and medium-sized transformers which are to be mounted upon poles, a device known as a **thermotel** is often used to indicate when the transformers are overloaded or operating at too high temperatures. This device can be read from the ground and therefore does not necessitate climbing the pole to determine the operating temperature of the transformer.

Fig. 112 shows a photograph of a thermotel unit which is equipped with an extension to be inserted under the cover of the transformer tank. These devices operate by the expansion of a liquid in a tube immersed in the oil. When the oil becomes heated the liquid expands and increases the pressure on the walls of a thin, curved, metal tube attached to the pointer of the device.

The increased pressure tends to straighten out the tube and thereby causes the pointer to move across the scale a certain distance, in proportion to the temperature of the transformer oil.

As this temperature is proportional to the amount of load, the scale of the thermotel can be marked so that the pointer will indicate the percentage of load or overload at which the transformer is operated.

If the transformer is overloaded and the pointer is caused to move beyond the 100% load mark, it trips a white vane or semaphore which falls into view in the window of the device. This indication is clearly visible to an inspector on the ground and shows that the transformer has been overloaded. These devices are exceptionally convenient because they can be read from the ground and can be installed on a transformer by simply hanging over the edge of the transformer case a hook-like extension which carries a tube of liquid.

Cent.	Fahr.	Cent.	Fahr.	Cent.	Fahr.	Cent.	Fahr.	Cent.	Fahr.
-40	-40	15	59	70	158	150	302	800	1472
-35	-31	20	68	75	167	160	320	900	1652
-30	-22	25	77	80	176	170	338	1000	1832
-25	-13	30	86	85	185	180	356	1200	2192
-20	-4	35	95	90	194	190	374	1400	2552
-15	+5	40	104	95	203	200	392	1600	2912
-10	+14	45	113	100	212	300	572	1800	3272
-5	+23	50	122	110	230	400	752	2000	3632
0	+32	55	131	120	248	500	932	2200	3992
+5	+41	60	140	130	266	600	1112	2400	4352
+10	+50	65	149	140	284	700	1292		

Fig. 111. This convenient table gives the comparative temperature values in degrees centigrade and Fahrenheit. With this table it is easy to convert the degrees centigrade from the rating or temperature of any electrical equipment into degrees of the Fahrenheit scale.

121. INSULATING BUSHINGS

Where the primary and secondary leads of the transformer coils are brought out of the tank or case for connection to the line, these leads must be carefully insulated from the metal case, in order to prevent flash-overs and grounding of the circuit.

On low-voltage transformers, ranging from 110 to 2300 volts, the insulated wires are brought out through small procelain bushings or collars, as shown in Fig. 106. On transformers operating at voltages from 2300 to 33,000 volts, much larger porcelain bushings are used. These bushings are equipped with flanges or petticoats to increase the creepage or flash-over distance which an arc would have to travel in order to jump from the lead-in wire to the tank.

Bushings of this type are shown on the high-voltage terminals of the transformers in Fig. 107 and 108. The low-voltage leads on both of these transformers are brought out through the ordinary small porcelain bushings.

On transformers operating at voltages from 50,000 to 220,000 volts or more, special oil-filled porcelain bushings or condenser-type bushings are used. The high-voltage bushings on the 220,000 volt transformers shown in Fig. 109 are of the oil-filled porcelain type. The porcelain of these bushings is hollow and is filled with oil, which is separated into layers by a number of thin insulating tubes.

High-voltage bushings of this type have a metal rod extending through them from one end to the other, to serve as a conductor. The coil and line leads are connected to the top and bottom ends of this rod by means of bolts or threaded connections.

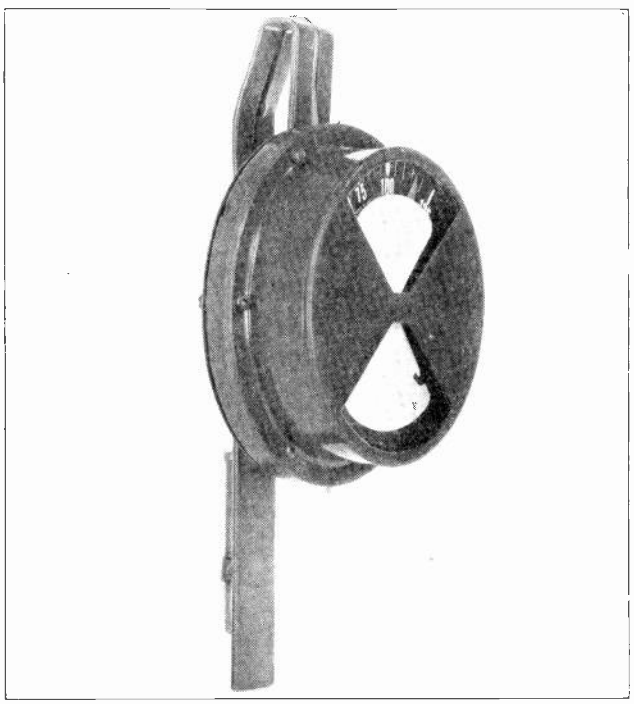

Fig. 112. This pho'o shows a temperature-indicating device for use with pole type transformers. This device is called a thermotel and indicates both excessive temperatures and overload of a transformer on which it may be installed.

The condenser-type bushing consists of a number of alternate layers of insulation and metal foil wrapped tightly around the conductor rod. The reason for using layers of metal foil in a bushing of this type, instead of using solid insulation, is that the metal distributes the voltage stress more evenly over the entire surface of the insulation layers and thereby reduces the tendency to puncture at one spot near the iron tank of the transformer.

Fig. 113 shows a polyphase transformer removed from its tank, but with the cover in place so the lower ends of the insulating bushings can be seen. The smaller bushings in the front are those of the low-voltage leads and the larger bushings in the rear are those of high-voltage leads.

You will also note that the connecting lead between the two outer windings is carried across through a special tube of insulating material, to prevent flashing over to the center coil.

Power transformers are built in voltages ranging from 110 to 220,000, while special testing transformers used in research and laboratory work are built to develop voltages as high as 250,000 or more from one unit.

A number of these transformers can be connected in series or cascade connection to obtain potentials as high as several million volts. Voltages of this order are used in making flash-over and puncture tests on line insulators, transformer bushings, high-voltage cables, etc. They are also used for determining the effects of lightning on transmission line equipment, electrical machinery, and buildings. Fig. 114 shows a demonstration of an arc from the high-voltage transformers which can be seen in the right rear of this photo.

Special industrial transformers are made to step voltages down as low as 1 or 2 volts and to produce

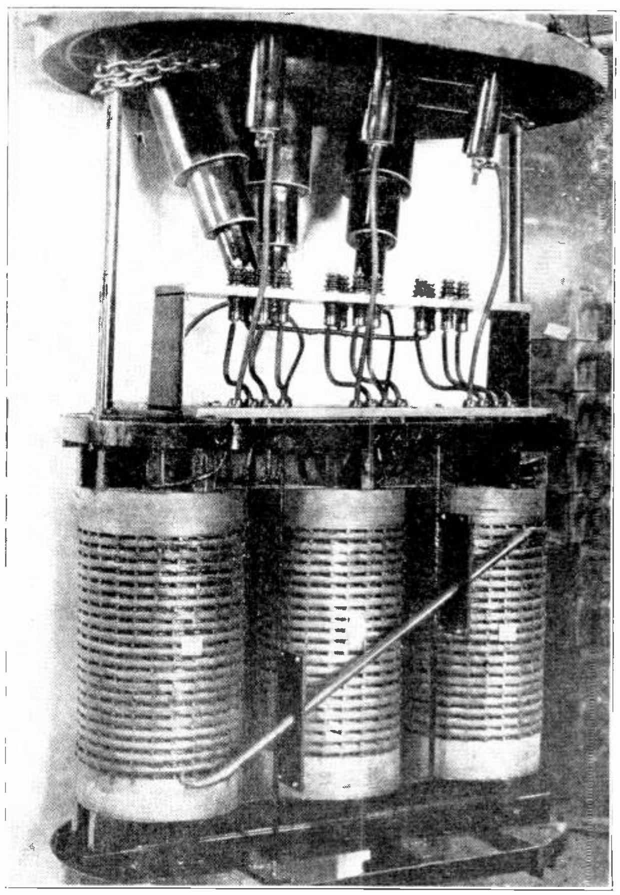

Fig. 113. This view shows the core and windings of a high voltage, three-phase transformer and also the lower ends of the insulating bushings through which the high voltage and low voltage leads are taken from the tank.

many thousands of amperes from very low voltage secondary windings, to be used in butt welding, spot welding, etc.

Transformers are rated in kv-a. and are built in sizes from a fraction of one kv-a. to 40,000 kv-a. or more.

122. TANSFORMER PRINCIPLES

When the primary winding of a transformer is excited with alternating current, the powerful magnetic field which is set up around this winding and through the core will cut across the turns of the secondary winding as the flux expands and contacts with the variations and reversals of the current in the primary winding.

As this flux cuts back and forth across the turns of the secondary winding, it induces a voltage in each of these turns by the principle of electro-magnetic induction which has already been explained.

As the induced voltage in the secondary coil depends upon the movement of the primary flux, and as this flux moves in synchronism with the alternations of the primary current, the secondary current will always be of the same frequency as that in the primary.

The secondary current will, however, always be approximately 180° out of phase with the primary current. This is due to the fact that the most rapid change of primary flux occurs during the period when the primary alternations are passing through or near their zero values, as was shown with the sine curves in Section One of Alternating Current.

It is at this point of most rapid flux change that the maximum voltage is induced in the secondary;

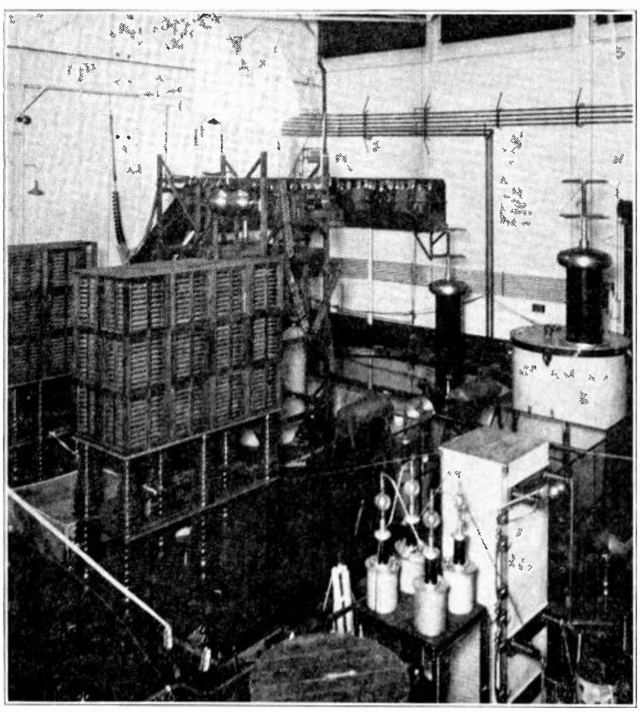

Fig. 114. The above photo shows a high voltage test room at the plant of the General Electric Company. Transformers in this room are capable of producing over one million volts and an enormous arc produced by this voltage can be seen above the sphere gap and condenser slightly to the left of the center of the picture.

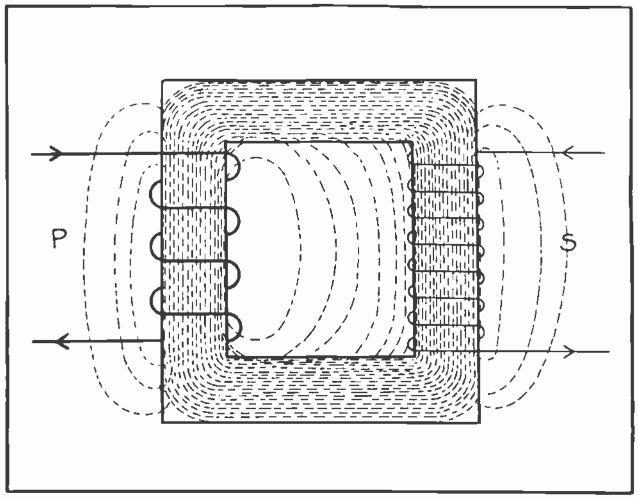

Fig. 115. This sketch illustrates the operating principle of a simple transformer and shows the manner in which the primary flux passes through the core and induces voltage in the secondary winding.

therefore, the maximum secondary voltage occurs approximately 90° later than the maximum primary current.

As a transformer winding is highly inductive and has very little resistance, the secondary current will lag approximately 90° behind the induced secondary voltage. Thus, the secondary current is approximately 180° behind the primary current. This is a very good point to remember because it means that when the current flows through the primary coil in one direction, as shown by the arrows in Fig. 115, it will be flowing in the opposite direction through the secondary coil.

Therefore, if the primary and secondary coils are wound alike, the voltage polarities produced at the ends of the secondary coil will be opposite to those applied to similar ends of the primary coil.

You will note in Fig. 115 that, while the greater part of the magnetic flux set up by the primary follows the iron core, a certain amount of this flux will be set up around the windings outside of the core and also across the opening between the core legs. This is called **leakage** flux and is considerably greater at full load of the transformer than at no load.

123. TRANSFORMER RATIOS AND SECONDARY VOLTAGES

In a simple transformer, all of the turns of the secondary coil are in series with each other, so their induced voltages will add together and the voltage at the terminals of the secondary winding will be the sum of the voltages induced in all the turns.

Therefore, **the greater the number of turns in the secondary winding of any transformer, the higher will be the voltage induced in this winding.**

From this, we find that in any transformer the amount of voltage change, or the ratio between the primary and secondary voltages, will be proportional to the ratio between the number of turns in the primary and secondary windings.

For example, if the primary winding of the transformer shown in Fig. 115 has fifty turns and the secondary winding has one hundred turns, the transformer will be a step-up transformer with a ratio of one to two.

The first figure of a transformer ratio always refers to the primary and the second figure to the proportional number of turns in the secondary.

If, in another case. we have a step down transformer with a primary winding of 1000 turns and a secondary winding of 100 turns, the ratio of this transformer would be expressed as 10:1; and if we were to apply 2200 volts to the primary winding, 220 volts would be produced by the secondary winding.

From these illustrations we can see that the following formula applies:

$$\frac{\text{Primary turns}}{\text{Secondary turns}} = \frac{\text{Primary voltage}}{\text{Secondary voltage}}$$

or, in the case of the transformer just mentioned,

$$\frac{1000}{100} = \frac{2200}{220}, \text{ or } \frac{10}{1} = 10:1$$

If we know the ratio between the number of turns on the primary and secondary windings of any transformer and know the amount of primary voltage which is applied, we can easily determine the secondary voltage, because it will bear the same relation to the primary voltage as the number of secondary turns bears to the number of primary turns.

To find the secondary voltage of either a step-up or step-down transformer, **divide the primary voltage by the ratio of primary to secondary turns,** or in other words,

Secondary E = (Primary E × last figure of ratio) ÷ first figure of ratio.

For example, if a step-up transformer with a ratio of 1 to 10, has 100 volts applied to its primary, the secondary voltage will be (100 × 10) ÷ 1, or 1000 volts.

If, in another case, a step-down transformer with a ratio of 20 to 1 has 2200 volts applied to its primary, the secondary voltage will be (2200 × 1) ÷ 20, or 110 volts.

The formula for finding the approximate secondary current is as follows:

Sec. I = (Pri. I × first figure of ratio) ÷ last figure of ratio.

124. POWER OUTPUT OF TRANSFORMERS

If a transformer were 100% efficient, the amount of power in kv-a. that would be obtained from the secondary would always be the same as that supplied to the primary, regardless of the amount that the voltage might be stepped up or down.

Of course, no transformer can be 100% efficient, but the efficiency of large power transformers is so high that for simple illustrative problems we may ignore the slight loss.

If a step-up transformer produces a secondary voltage ten times as high as the voltage applied to the primary, then the full load current in the secondary winding will be just one-tenth of that in the primary winding.

For example, if a 10 kv-a. transformer with a ratio of 1 to 10 has 200 volts and 50 amperes applied to its primary and increases the voltage to ten times higher, or 2000 volts on the secondary, the full load secondary current will then be 5 amperes.

If we multiply the volts by the amperes in each case, we will find the same number of volt-amperes or kv-a. in the secondary as in the primary. The primary voltage times primary current will be:

200 × 50 = 10,000 volt-amperes, or 10 kv-a.

The secondary volts times the secondary amperes will be:

2000 × 5 = 10,000 volt-amperes, or 10 kv-a., as before.

From this, it is evident that the high-voltage winding of any transformer can be wound with correspondingly smaller wire, according to the ratio between the high-voltage and low-voltage windings. Therefore, the high-tension winding of any transformer is always the one with the smaller wire and the greater number of turns; while the low tension winding is the one with the larger wire and the smaller number of turns.

This has been mentioned previously but it is repeated here as a reminder of a very simple way to determine which is the high-voltage coil and which is the low voltage coil of any transformer.

As power factor doesn't enter into the kv-a. rating of a transformer or into the calculations for volt-amperes, it is a simple matter to find the current rating of any transformer winding merely by dividing the volt-amperes by the voltage of that winding.

To obtain the volt-amperes, remember, it is only necessary to multiply the kv-a. rating by 1000, as one kv-a. equals 1000 volt-amperes.

One volt-ampere is the same as one watt of apparent power. For example, if we have a 10 kv-a. transformer with a ratio of five to one, and a primary voltage of 550, the secondary voltage would be 110 volts. If we multiply the kv-a. rating of 10 by 1000, we get 10,000 volt-amperes. The primary current will then be 10,000 ÷ 550, or 18.2 amperes, and the secondary current will be 10,000 ÷ 110, or 91—amperes.

If the power factor of a transformer were 100%, we could obtain the same number of actual kw. of true power as the kv-a. rating of the transformer. However, the power factor of a transformer and its attached load is usually much lower than 100%, so it is often possible to have a 10 kv-a. transformer fully loaded and yet supplying only 5 to 8 kw.

This is the reason transformer capacity is always rated in kv-a.

125. EFFECT OF SECONDARY LOAD CURRENT ON PRIMARY CURRENT

When a transformer is operating idle, that is, connected to the line but having no load connected to the secondary, only a very small amount of current will flow in the primary winding. This current is called the **magnetizing current** and is just the amount required to strongly magnetize the core.

As long as a transformer is not loaded, the lines of force of this very strong field set up by the magnetizing current are constantly cutting across the turns of the primary winding and thereby inducing a counter-voltage which is very nearly equal to the applied voltage. This limits the current flow to a very small amount.

As soon as the load is connected to the secondary, the primary current will automatically and immediately increase in proportion to the amount of this load. If the secondary is fully loaded, the primary current immediately comes up to full load value. If the secondary is overloaded the primary will also be overloaded, and it is thus possible to burn out the primary or both the primary and secondary windings by connecting too much load to the secondary of any transformer.

This automatic variation in the current taken by the primary whenever the load on the secondary is changed, is caused by the reaction of the secondary flux on the flux of the primary coil. When there is no load connected to the secondary winding there will, of course, be no current flowing through it, even though full voltage is induced in this winding. As soon as its circuits is closed by connecting some load to the secondary leads, current starts to flow through this winding and sets up a magnetic field around it.

We recall that the current in the secondary winding is always 180° out of phase or in the opposite direction to that in the primary; therefore, the magnetic flux set up by the secondary is in the opposite direction to the primary flux in the core.

This secondary flux neutralizes a certain amount of the primary flux and reduces the number of lines of force which are cutting across the primary turns. This reduces the counter-voltage set up in the primary and allows more current to flow through it.

The resistance of the primary winding is so low as to be almost negligible, so the transformer depends largely upon the counter-voltage of self-induction to limit the current flow through this winding.

If the secondary load is increased to such an extent that the flux of its currents neutralizes a large part of the primary flux, the counter-E.M.F. generated in the primary winding will be so low that an excessive flow of current will result and possibly burn out the winding.

This is a very important principle to keep in mind in connection with transformers and certain other alternating current machines. It explains the reason why A. C. windings will usually be burned out very quickly if connected to a D. C. circuit; because direct current, with its constant and unchanging flux, doesn't develop counter-voltage to limit the current flow.

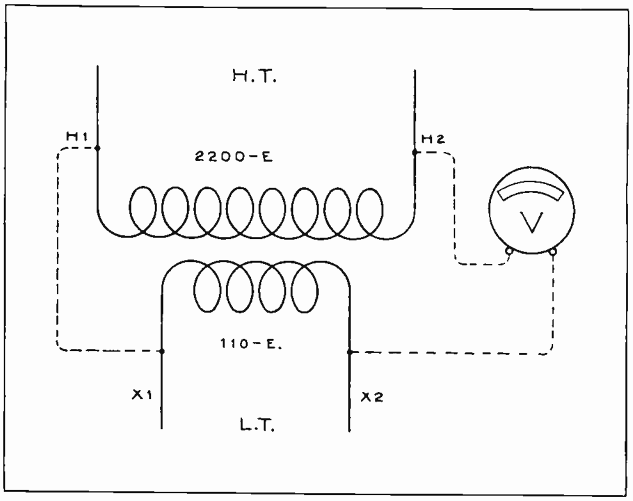

Fig. 116. This diagram shows the methods of connecting a shunt and a voltmeter to the high tension and low tension terminals of a transformer for making a polarity test.

126. POLARITY OF TRANSFORMER LEADS

Nearly all modern transformers have their H.T. and L.T. leads marked with **polarity markings.** These marks would be for example: H-1 and H-2 on the high-tension side of a single-phase transformer, and X-1 and X-2 on the low tension side.

On a three-phase transformer, the leads would be marked H-1, H-2, and H-3 on the high-tension side; and X-1, X-2, and X-3 on the low-tension side. These polarity markings indicate the order in which the leads are brought out from the windings, and also indicate the respective polarities of primary and secondary leads at any instant.

We know, of course, that the polarity of alternating-current windings is continually and rapidly reversing; but, as the secondary always reverses with the same frequency as the primary and is always 180° out of phase with the primary, we can determine the respective polarities at any instant of any alternation.

These polarity markings aid in making the proper connections for transformers to be operated in parallel, as it is necessary to have similar leads connected together, in order to have the transformers operate with the proper phase relations for satisfactory parallel operation.

If a transformer winding is marked H-1, H-2, H-3, and H-4, it will usually be found that H-1 and H-4 indicate the end-leads or full-winding terminals, while H-2 and H-3 are intermediate taps taken off at certain sections of the winding. If transformers are connected in parallel with wrong polarity they will burn out or blow the fuses.

The highest and lowest numbers are placed at the end-leads or full winding, while the intervening numbers are placed on the part-voltage taps. The H-1 lead is usually located on the right-hand side, when facing the high tension side of the transformer. With transformers marked in this manner, if the H-1 and X-1 leads are connected together, as shown by the dotted line in Fig. 116, then when the voltage is applied to the H.T. winding the voltage between the remaining X-2 and H-2 leads will be less than the full voltage of the high-voltage winding.

In Fig. 116 a voltmeter is shown connected across the H-2 and X-2 leads of the single-phase transformer. The reason its reading will be lower than the applied voltage on the primary winding is because the polarity of the low-voltage winding is opposite to that of the high-voltage winding, and the two voltages will therefore oppose each other; so that the voltmeter will read their difference; or 2200 — 110 equals 2090. A transformer with the leads arranged and marked in this manner is said to have **subtractive polarity.**

If the leads are brought out of a transformer so that the voltmeter when connected to the adjacent H and X leads, as shown in Fig. 116, reads the sum of the voltages of the high tension and low tension windings, then the transformer is said to have **additive polarity.** In this case the markings of the X-1 and X-2 leads would be reversed.

On transformers which have their leads properly marked, the markings indicate whether the leads are arranged for subtractive or additive polarity.

Fig. 117 shows on the left a transformer with the leads marked for subtractive polarity and on the right another transformer with the leads marked for additive polarity.

When facing the high-tension side of a transformer, if the X-1 lead is on the right-hand side, it indicates that the polarity is subtractive; while, if the X-1 lead on the left, it is then known to be additive polarity.

Leading transformer manufacturers have adopted standard connections and polarity markings for their transformers. Most power transformers are arranged with subtractive polarity, except distribution transformers of 200 kv-a. and under and with voltage ratings of 7500 volts and less; and these transformers are arranged with additive polarity.

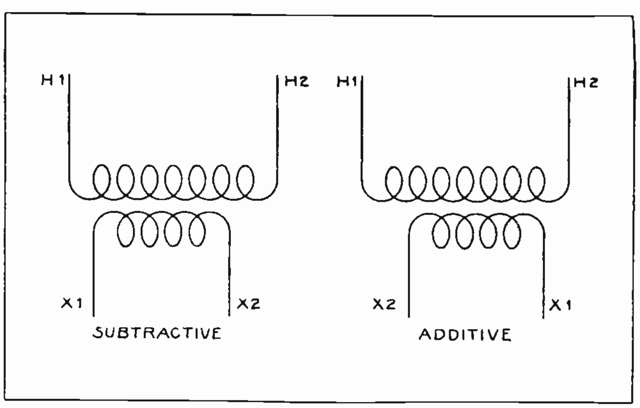

Fig. 117. This sketch shows windings of two transformers with their leads properly marked for subtractive and additive polarities.

127. VOLTMETER TEST FOR TRANSFORMER POLARITY

When the leads of a transformer are not marked in any manner, we can determine whether it has additive or subtractive polarity by simply connecting a jumper between the high-tension and low-tension leads on one side and a voltmeter of the proper rating between the high-tension and low-tension leads on the other side, as shown in Fig. 116.

If, when the primary is excited with its rated voltage, the voltmeter reads the difference between the voltages of the high and low voltage windings, the transformer has subtractive polarity, and the leads should be marked as shown in Fig. 116.

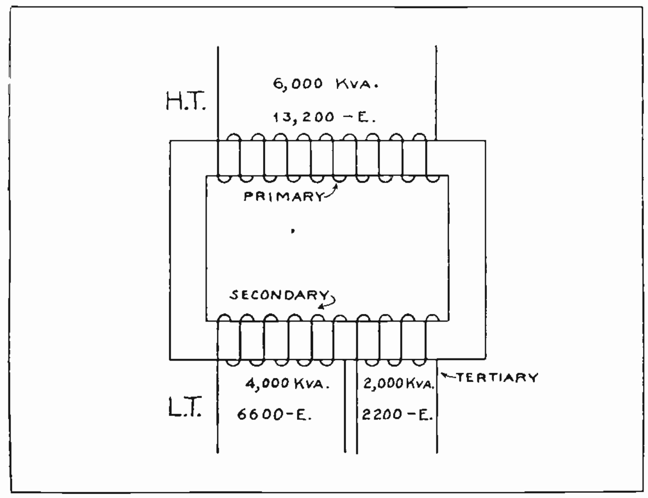

Fig. 118. Diagram of a transformer which is equipped with three windings. The high tension winding in this case is the primary, and the low tension winding is divided into two sections, called the secondary and tertiary windings.

If the voltmeter reads the sum of the voltages of the high and low voltage windings, the transformer has additive polarity, and the leads should be marked as shown in the sketch at the right in Fig. 117.

Sometimes a transformer may have on its core a third winding which really acts as an additional secondary winding and is for the purpose of supplying a separate circuit of a different voltage. This third winding is commonly called a **tertiary** winding.

Fig. 118 shows a transformer with primary, secondary, and tertiary windings. The primary winding is designed for 6000 kv-a. at 13,200 volts. The secondary winding, or larger of the two low-tension windings, is designed for 4000 kv-a. at 6600 volts. The tertiary winding, or smaller of the two low-tension windings, is designed for 2000 kv-a. at 2200 volts.

Some special transformers may also use tertiary windings to obtain certain power factor and voltage control characteristics.

TRANSFORMER CONNECTIONS

Transformers can have their primary and secondary windings connected in a number of different ways, using series and parallel connections to obtain different voltages, current capacities, etc. A number of the most common connections are thoroughly explained in the following paragraphs and illustrated with the accompanying diagrams. Observe each of these connections carefully and note the results obtained and the purpose for which each connection is used. Connections for single-phase transformers will be covered first and those for polyphase and special transformers will follow.

Fig. 119 shows a sketch of the windings and leads of an ordinary single-phase transformer, such as is commonly used for supplying current to lights and small motors. This transformer has a ratio of 20:1, with the primary winding designed for 2300 volts for connection to the regular 2300-volt distribution lines which are commonly run down streets or alleys to supply power to homes and small shops.

The secondary winding is designed for 115 volts and has two leads for connection to the service wires running to the house or shop. The outline of the tank is shown by the dotted line surrounding the windings.

The high-tension and low-tension leads are usually brought out on opposite sides of the tank, as shown in this diagram. The position and manner in which these leads are brought out was also clearly shown on the two smaller transformers in Fig. 106. Refer back to this photograph so that you may note and have well in mind the manner in which these leads are brought out at the top of the transformer case.

In Fig. 119, one side of the low-voltage secondary winding is shown grounded. This is done for safety reasons and to provide the grounded wire for polarized lighting systems, as previously explained in the section on wiring for light and power. It is well to mention again that this ground affords a definite safety protection against damage to connected equipment or accident to persons, in case of failure of the insulation between the high-voltage and low-voltage windings.

For this reason, the ground wire which is attached to the secondary wire and carried down the pole to a ground rod should be carefully connected and protected from breakage or damage.

129. SINGLE-PHASE TRANSFORMERS WITH SPLIT SECONDARIES

Most single-phase transformers are made with the secondary winding in two sections and have four leads brought out from this winding. This allows a choice of two voltages for light and power purposes, and also provides connections to obtain a three-wire Edison system with grounded neutral for lighting purposes.

Secondary windings arranged in this manner are known as **split-secondary, or series-multiple** secondary, windings. Fig. 120-A shows a diagram of a transformer of this type and also shows the manner in which the center leads of the split-secondary are usually crossed inside the transformer tank. This is done for convenience in connecting them in either series or parallel outside of the tank.

Fig. 120-B shows how the two sections of the secondary winding can be connected in series by simply connecting the two center leads together on the outside of the tank. Each half of the secondary is designed to supply 115 volts, so that when the two are connected in series, 230 volts will be obtained across the outside wires and 115 volts across either outside wire and the center wire.

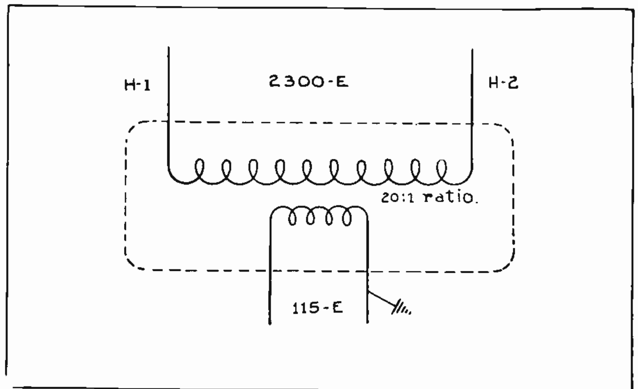

Fig. 119. The above sketch shows a schematic diagram of the primary and secondary windings of a single-phase transformer. This transformer has a step-down ratio of 20:1 and one side of the secondary is grounded, as is common practice.

If only 230-volt service is desired, the center wire can be left off and just the two outside wires used, but if three-wire, 115-volt and 230-volt service is desired, the center wire is connected to the point where the secondary coils are joined together, as shown. The ground connection should be attached to the center point when the three-wire system is used, and can be attached either to the center or to one of the outside wires when 230-volt, two-wire service is used.

Fig. 120-C shows the manner in which the two secondary windings can be connected in parallel to supply 115 volts and double the current capacity of either winding. This makes the entire output of the transformer available at 115 volts.

You will note from this diagram that having the center leads crossed inside the transformer makes possible a very convenient parallel connection by simply connecting together the adjacent leads outside of the tank.

The connections shown in Fig. 120-B for providing 115 and 230-volt service, brings three wires from the secondary of the transformer. The circuit, however, remains single-phase and should never

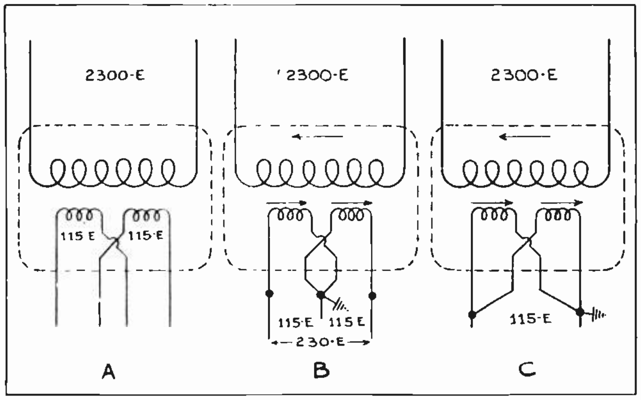

Fig. 120. A shows a single-phase transformer with the secondary winding in two sections. Note the manner in which the leads are crossed inside of the tank. B, Secondary windings connected for 115 and 230-volt service. C, Secondary windings connected in parallel for 115-volt service.

be confused with a three-phase transformer just because they both have three wires.

Keep in mind when connecting load to a three-wire system, that **the load should be balanced as evenly as possible** between each outside wire and the neutral, in order to prevent operating one side of the transformer secondary heavily loaded while the other is idle or lightly loaded.

The arrows shown above the windings in Figs. 120-B and 120-C indicate the direction of the voltage that would be induced in the secondary coils with respect to the voltage in the primary at a certain instant when the right-hand primary wire is considered to be positive.

These arrows will show how the voltages of the two secondary coils add together in Fig. 120-B and how the currents would add together in Fig. 120-C.

130. TESTING SPLIT-SECONDARY LEADS BEFORE MAKING CONNECTIONS

In connecting the two coils of the secondary winding of a transformer in either series or parallel, if there is any doubt as to the way connections have been brought out of the tank, the leads before being connected together should be carefully tested by means of test lamps or a voltmeter.

To test them for finding the proper leads to connect in series, connect together two leads, one from each coil, and then connect a lamp or voltmeter between the remaining two leads. If when the primary is excited, the lamps burn brightly or the voltmeter indicates the sum of the voltages of the two secondary windings, the connection is correct for series operation.

The first two leads which were joined can then be permanently connected together, and the line wires connected to the two wires to which the lamp or voltmeter were attached.

In testing the leads for parallel connection, again temporarily join together one lead from each coil and connect the lamps or voltmeter between the remaining two leads. If when the primary is excited, the lamps do not burn or the voltmeter shows no indication, the leads to which they are connected may be safely joined together to one of the line wires for parallel operation. The other leads can be permanently connected together and attached to the opposite line wire.

If the lamps light or the voltmeter indicates voltage, the leads are improperly connected and should be reversed before being permanently connected for parallel operation.

It is very important that the proper leads be used when connecting transformer secondaries in parallel; otherwise, the windings will probably be burned out when the primary is excited.

131. PARALLELING SINGLE-PHASE TRANSFORMERS

Two or more single-phase transformers can be connected in parallel to supply a greater current or kv-a. of power than the capacity of one transformer will provide. In this manner additional transformers can be installed to take care of increasing load which has grown beyond the capacity of transformers already installed, or two or more small transformers can be temporarily connected in parallel to replace one larger transformer in emergencies when the larger transformer is to be taken out of service for repairs.

In paralleling transformers it is necessary to connect together transformers of similar characteristics; otherwise, one transformer may assume more than its share of the load and possibly blow the primary fuses. This would throw all of the load on the remaining transformers and would either overload them, or blow the fuses in their primary leads.

It is also very important to see that leads of the proper polarity are connected together; because, if the wrong secondary leads are connected in parallel, it would result in a double-voltage short-circuit, the same as though two single-phase alternators were connected in parallel when 180° out of phase.

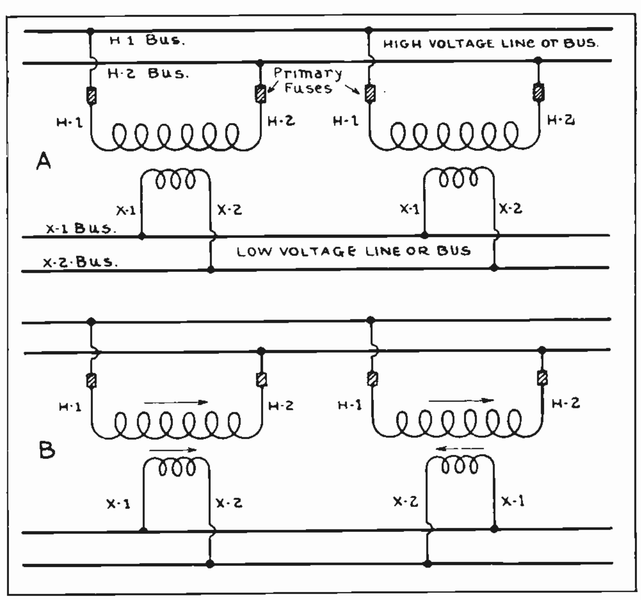

Fig. 121. A shows two single-phase transformers with like polarities connected in parallel. B shows the proper method of connecting two single-phase transformers in parallel when the polarity of one is subtractive and the other is additive. Note the polarity markings in each case.

Transformers with different ratios should never be connected in parallel, as even a small difference in the secondary voltages of two or more transformers would result in very heavy cross currents between the units if they were connected together.

When the primary and secondary leads are properly marked, it is a simple matter to connect two or more single-phase transformers in parallel, as leads with like polarity markings can then be safely connected together, as shown in Fig. 121-A.

In connecting together two transformers, one of which has additive polarity and the other subtractive polarity, the leads should be arranged in parallel, as shown in Fig. 121-B.

132. TESTING SECONDARY LEADS FOR PARALLELING SINGLE-PHASE TRANSFORMERS

If the leads of the transformers are not marked, then the secondary leads should be tested with a voltmeter or lamp bank before being connected in parallel. This test is illustrated in Fig. 122, and is similar to the tests made for parallel connections of the two secondary windings of one single-phase transformer.

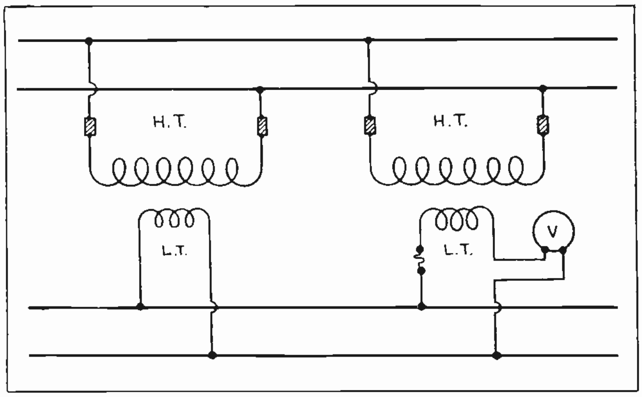

Fig. 122. This diagram illustrates the method of using a voltmeter to test the polarity of a transformer secondary before connecting it in parallel with another.

The high-tension leads can be connected to the supply line in a uniform manner, as shown in the diagram. The secondary leads of one transformer can then be connected to the low-voltage line, and the secondary leads of the other transformer should have an instrument fuse connected in one and a voltmeter connected in the other; then they can be connected to the line in the same manner as those of the other transformer.

If the voltmeter shows no reading, the connections are correct for parallel operation and the fuses can be eliminated and the voltmeter removed from the circuit. If the voltmeter does show a reading, the connections are wrong and the leads of one transformer secondary should be reversed and then connected to the line after testing again with the voltmeter to make sure that they are right.

133. CONNECTING TRANSFORMER PRIMARIES IN SERIES

In certain cases it might be desired to connect a back of single-phase transformers to a high-tension line which has a voltage higher than the voltage rating of the high-tension winding of the transformers. As the more common distribution and transmission voltages usually vary in multiples such as 2200 volts, 6600 volts, 13,200 volts, etc., it is often possible to connect the primaries of two or more transformers in series to the high-voltage line. The secondaries can then be connected in parallel or series as desired.

Fig. 123 shows three single-phase transformers with 2200-volt primary windings connected in series to a 6600-volt line. The impedance of the three windings in series is the same as that of one 6600-volt winding of the same kv-a. capacity and will therefore limit to the proper value the current which will flow through the windings at 6600 volts.

The secondaries of these three transformers are shown connected in parallel to the low-voltage line. If each of the transformers has a 10:1 ratio, the low-voltage line will be supplied with 220 volts and the power that can be taken from this line will be equal to the sum of the kv-a. ratings of the three transformers. The extent to which such series connections can be applied is limited by the insulation between the transformer coils and ground.

Fig. 124 is a photograph of a transformer installed on a pole, and shows the method of connecting the low-voltage secondary leads together and to the wires which run to the buildings for three-wire service. You will also note the lightning arresters which are attached to the high voltage wires and have their lower ends grounded, and the fuse cutouts which are mounted on the rear cross-arm and connected in series with the primary leads.

This view also shows the installation of a thermotel temperature and load indicator which is inserted under the edge of the transformer tank cover.

134. THREE-PHASE TRANSFORMER CONNECTIONS

To step the voltage of a three-phase circuit up or down, it is necessary to use either a polyphase transformer or three single-phase transformers; except in certain cases where, by means of special connections, two single-phase transformers can be used.

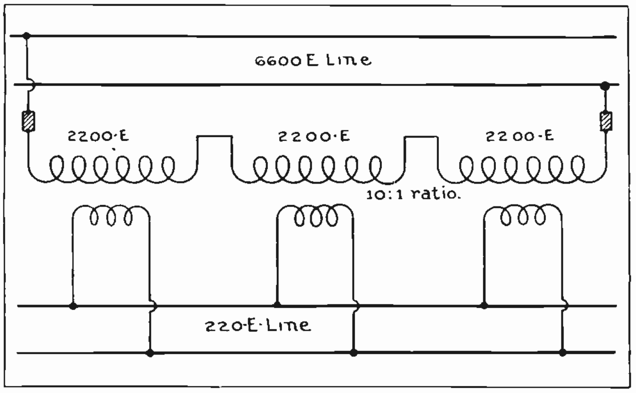

Fig. 123. Transformer primaries are sometimes connected in series to a line of higher voltage as shown above. The secondaries can then be connected for parallel operation.

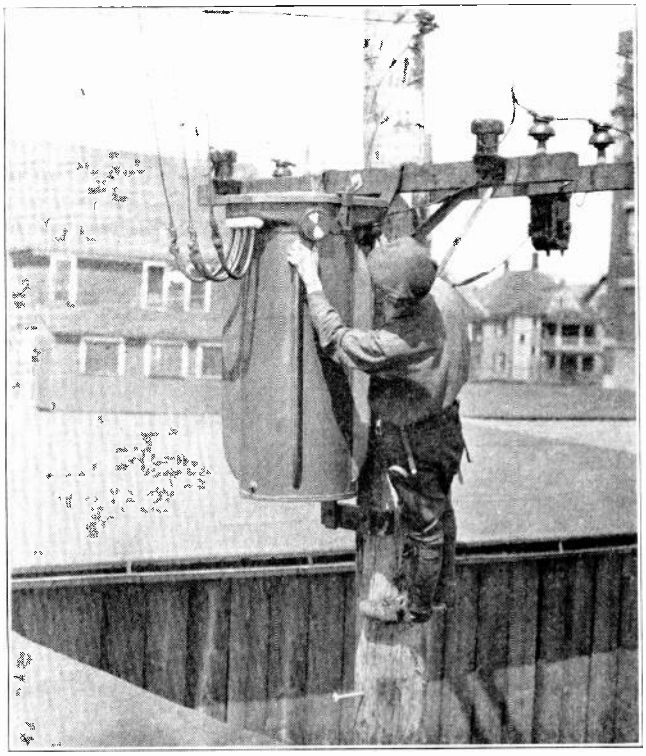

Fig. 124. This photo shows a pole type transformer and the method of making primary and secondary connections. Also note the thermotel temperature indicator near the hand of the electrician.

Each method will be explained in the following paragraphs.

Polyphase transformers are quite commonly used where space is limited, because they are more compact and require less space than three single-phase transformers of the same kv-a. rating.

Where flexibility is desired, three single-phase transformers are frequently used because of the advantage in the fact that if one transformer is taken out of service the load can be temporarily carried by the other two, by making a slight change in the connections.

Fig. 125 shows the arrangement of the primary and secondary coils on the core of a three-phase step-down transformer. This sketch also shows the connections of the primary and secondary windings to high-voltage and low-voltage three-phase lines.

In each of the following connection diagrams three primary and three secondary windings will be shown without the cores, and these can be used to represent either three single-phase transformers or the three sections of a three-phase transformer.

When three single-phase transformers are connected together to a three-phase system they are commonly referred to as a **bank** of transformers.

135. STAR AND DELTA CONNECTIONS, AND THEIR VOLTAGE AND CURRENT RATIOS

There are three types of connections commonly used with transformers on three-phase systems, and these connections are known as the **star, delta,** and **open-delta** connections.

Ordinary star and delta connections and their voltage and current ratios have been explained both in the second section on Armature Winding and in the first section on Alternating Current, in connection with A. C. motor and generator windings. The same ratios and values for these connections apply to transformers as well as to motors or generators, and they will therefore be repeated here for convenience.

You will recall that the star connection provides a sort of series arrangement of the windings of any electrical machines connected in this manner; while the delta connection is a parallel arrangement of the windings.

The star connection always increases the line voltage above that of the phase windings, while the delta connection increases the line current above that of the phase windings.

When transformer or generator windings are connected **star,** the **line voltage will be 1.732 times the phase-winding voltage** and the **line current** will be the **same as the phase-winding current.**

When transformers or generators are connected **delta,** the **line current will be 1.732 times the phase-winding current** and the **line voltage** will be the **same as that of the phase windings.**

We recall that multiplying either the current or voltage by the constant 1.732 gives the actual sum of two values which are added together 60° out of phase. Note.—These values are 60° out of phase in the machine windings, but 120° out of phase with the line. To make it very easy to determine the voltage or current that can be obtained by the use of star or delta connections with transformers, we can arrange the material from the preceding statements in the following simple rules.

Rules for Star connections:

(A) Line I = Phase I
(B) Phase I = Line I
(C) Line E = Phase E $\times$ 1.732
(D) Phase E = Line E $\div$ 1.732

Rules for Delta connections:

(A) Line E = Phase E
(B) Phase E = Line E
(C) Line I = Phase I $\times$ 1.732
(D) Phase I = Line I $\div$ 1.732

136. THREE-PHASE STAR CONNECTIONS

Fig. 126 shows a diagram of the connections for either three single-phase transformers, or the three sets of windings of a polyphase transformer, in which both the primaries and secondaries are connected star, or Y.

This connection is known as the **star-star** or **Y-Y** connection.

You will note that, with this connection, the right-hand ends of each of the transformer windings are connected together to one common point or wire, and the left-hand ends are connected separately, one to each phase wire of the lines.

Tracing out this connection from each line wire through the phase windings, you will find it results

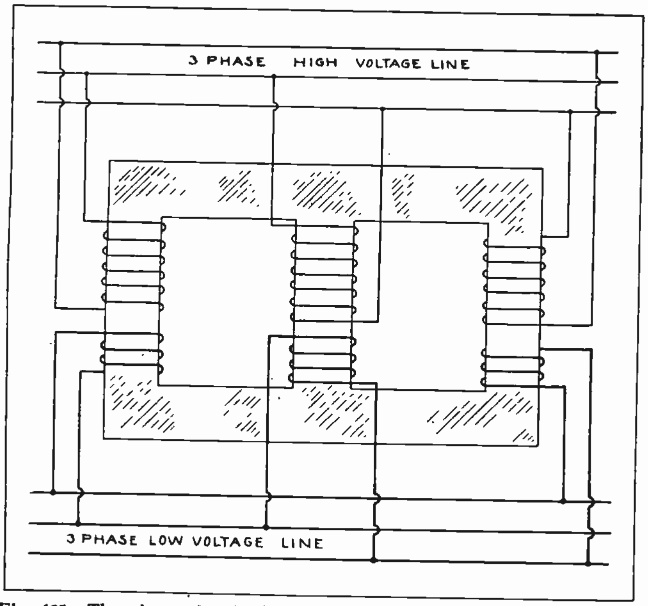

Fig. 125. The above sketch shows the primary and secondary windings of a three-phase transformer. Both primary and secondary are connected delta to the line wires.

in a star-shaped connection, as shown by the small simplified sketch at the left in Fig. 126.

To remember how to make this star connection, it is only necessary to keep in mind that **one end of each winding is connected to a common wire or neutral point** and that **the remaining ends are connected in order to respective phases.**

Where transformers are placed in an ordinary row or bank and where they have their terminals arranged and marked symmetrically, the connections to the high-voltage and low-voltage lines can usually be made in the same neat and symmetrical order as shown in Fig. 126. Following a definite and orderly system in this manner whenever possible, will help you to avoid mistakes when making such connections.

With this connection the primary line voltage will be found between L A and L B, L B and L C, and between L C and L A. This line voltage can also be found between any two of the three phase wires, A, B, and C.

The primary phase voltage is the voltage between L A and D, L B and D, and L C and D.

The secondary line voltage can be measured between S A and S B, between S B and S C, or between S C and S A.

It can also be measured between any two of the three phase wires, A, B, and C.

The secondary phase voltage can be measured between S A and E, S B and E, or S C and E.

For the purpose of illustrating the various voltage and current values on the primary and secondary line leads and phases, we shall assume that the primary line voltage is 1000 volts and the primary line current 10 amperes; and that the step-down ratio of the transformers is 10:1.

Then, according to rule D for Y connections, the primary phase voltage will be: 1000 ÷ 1.732, or 577 volts across each phase winding.

According to rule B for the current in Y connections, the primary phase current will be 10 amperes. Then, considering the 10:1 ratio, the secondary phase voltage will be 577 ÷ 10, or 57.7 volts.

The secondary current will be increased in the same proportion that the voltage is decreased; so that the secondary phase current will be 10 × 10, or 100 amperes through each phase winding.

The secondary line voltage will be 57.7 × 1.732, or 99.9+ volts.

According to rule C for Y connections, the secondary line current will be the same as that in the phase windings, or 100 amperes. According to rule A for Y connections, the apparent power in the secondary line would be equal to the apparent power in the primary line, minus the very small percentage of loss in the transformers. When the transformers are operating at or near full load, this loss is so small that it is generally not considered in the ordinary approximate calculations used in field problems.

To calculate the power of the three-phase bank of transformers from the primary line voltage and current, we would use the three-phase power formula given in Section One of Alternating Current, or:

Three-phase app. power = E × I × 1.732

With the values given in Fig. 126 this would be:

1000 × 10 × 1.732, or 17.3+ kv-a.

Following the same rule for the secondary, we would have:

99.9 × 100 × 1.732, or 17.3+ kv-a.

If the primary line voltage used on a star connection such as shown in Fig. 126 were 4000 volts instead of the 1000 volts assumed in this problem, then the primary phase voltage would be 4000 ÷ 1.732, or approximately 2309 volts across the primary winding of each transformer.

This voltage is very commonly used where the primaries of three transformers are to be connected in star and the secondaries used separately for sup-

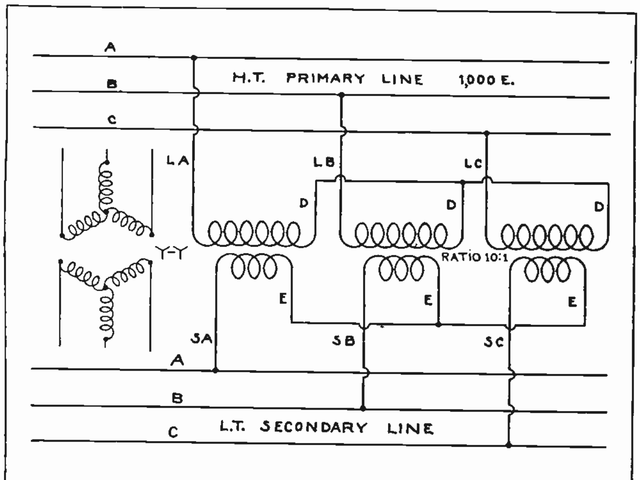

Fig. 126. Connection diagram for a bank of three transformers connected star-star.

plying single-phase light and power load at 115 and 230 volts.

137. THREE-PHASE DELTA CONNECTIONS

Fig. 127 shows the connections for a bank of three single-phase transformers, or the three sets of windings of a three-phase transformer, which are connected delta-delta, or Δ-Δ. These transformers are also of the 10:1 step-down ratio, and we shall assume the same values of 1000 volts and 10 amperes on the primary line.

If the primary line voltage is 1000, then, according to the rule B for delta connections, the primary phase voltage is also 1000. According to rule D for delta connections, the primary phase current will be 10 ÷ 1.732, or 5.77 amperes through each phase winding.

With the 10:1 step-down ratio, the secondary phase voltage will be 1000 ÷ 10, or 100 volts from "c" to "d" across each phase winding, and the secondary phase current will be 10 × 5.77 or 57.7 amperes through each phase winding.

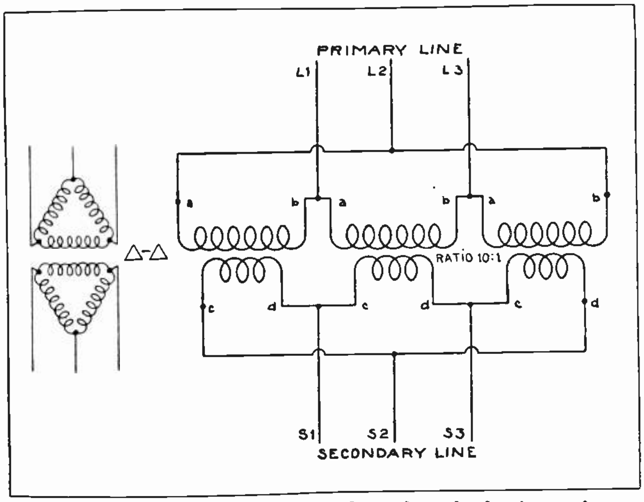

Fig. 127. Connection diagram for a three-phase bank of transformers connected delta-delta. Compare the large diagram with the small schematic sketch at the left and also with the explanation given in these paragraphs.

According to rule A for delta connections, the secondary line voltage will be 100; and according to rule C for delta connections, the secondary line current will be 57.7 × 1.732, or 99.9+ amperes.

The apparent power in kv-a. will again remain the same on the secondary as on the primary, with the exception of the slight loss in the transformers. So we find that it makes no difference in the amount of power the transformer will handle whether it is connected star or delta.

When a bank of transformers are connected either star-star or delta-delta, the difference between their primary and secondary line currents and voltages will only be that difference which is caused by the ratio between the transformer windings.

138. THREE-PHASE STAR-DELTA CONNECTIONS

Fig. 128 shows a bank of three transformers connected star-delta, or Y-Δ. The phase winding leads and line leads are marked the same in this diagram as in Fig. 127, and this transformer is also a step-down transformer with a ratio of 10:1.

We shall again assume the primary line voltage to be 1000 and the primary line current to be 10 amperes. With this connection, the primary phase voltage will be 1000 ÷ 1.732, or 577 volts between "a" and "b", or across each phase winding.

The primary phase current will be the same as the line current, or 10 amperes. With the 10:1 step-down ratio, the secondary phase voltage across each phase winding, or between "c" and "d", will be 577 ÷ 10, or 57.7 volts. The secondary phase current will be 10 × 10, or 100 amperes.

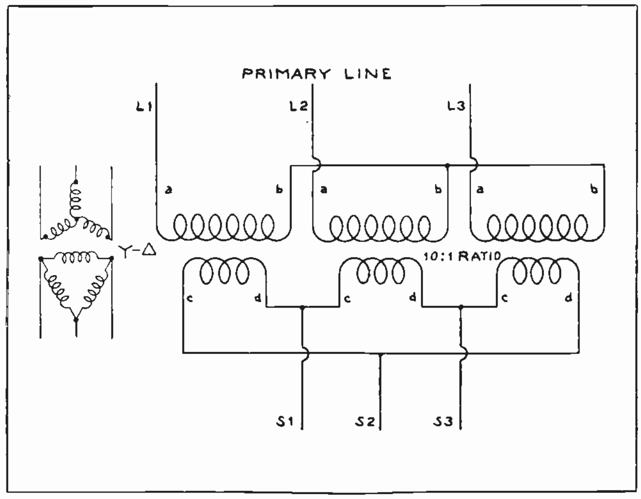

Fig. 128. Three-phase transformer bank with the primary connected star and the secondary delta. This connection is called "star-delta."

The secondary line voltage will be the same as the secondary phase voltage, or 57.7; because the secondary is connected delta. Check this with rule A for delta connections.

The secondary phase current will be 10 × 10 or 100 amperes, and the secondary line current will be 100 × 1.732, or 173.2 amperes, according to rule C for delta connections.

139. DELTA-STAR CONNECTIONS

Fig. 129 shows a bank of three transformers connected just the opposite to those in Fig. 128. In this case, the primary is connected delta and the secondary is connected star. This is called a delta-star or Δ-Y connection.

You will note that in referring to these connections with the terms delta or star, the primary is always mentioned first; the same as when speaking of the ratio between primary and secondary windings.

Assuming the same figures of 1000 volts and 10 amperes on the primary line and a 10:1 step-down ratio for these transformers in Fig. 129, the primary phase voltage will be 1000 from "a" to "b" in any phase winding, according to rule B for delta connections. The primary phase current will be 10 ÷ 1.732, or 5.77 amperes through each phase winding, according to rule D for delta connections.

With the 10:1 step-down ratio, the secondary phase voltage will be 100; and the secondary phase

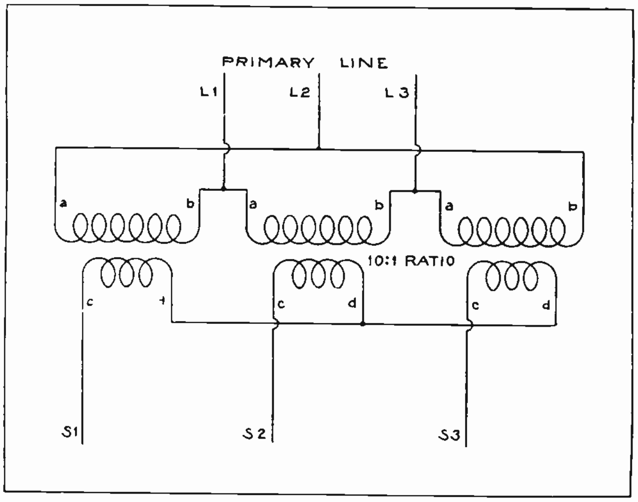

Fig. 129. Three-phase transformer bank connected delta-star. Observe carefully the methods of making the connections shown in each of the diagrams in this section.

current will be 10 × 5.77, or 57.7 amperes. The secondary is connected star; so, according to rule C for star connections, we find that the secondary line voltage will be 100 × 1.732, or 173.2 volts.

This voltage would be found between S-1 and S-2, or between S-2 and S-3, or S-3 and S-1.

The secondary line current will be the same as the phase current, or 57.7 amperes. Check this with rule A for star connections.

If you determine the apparent power in kv-a. of both the primary and secondary windings in either Fig. 128 or Fig. 129, by using the formula,

three-phase app. power =
Line E × Line I × 1.732,

and using the voltage and current values given for the lines in each case, you will find the power to be the same on the secondaries as on the primaries.

This will be very good practice and will help you to become more familiar with the use of the three-phase power formula and calculations.

The four transformer connections which have just been explained and illustrated are the ones most commonly encountered in the field. Some companies may make slight variations or changes in these, but the general principles involved remain the same.

140. ADVANTAGES OF STAR CONNECTIONS FOR TRANSMISSION LINES

One of the principal advantages of the star connection for transformers is that it provides higher voltages for use on long-distance transmission lines, with the lower ratios between the primary and secondary windings.

When used in this manner, the transformer supplying the power to the line is usually connected delta-star, to step up the voltage as high as possible with a given transformer ratio. The transformer at the receiving end of the line can then be connected star-delta, in order to reduce the voltage the maximum amount with a given transformer ratio.

Fig. 130 illustrates the use of these connections with a transmission line. A power plant alternator develops 2300 volts which is fed to the delta-connected primary of the step-up transformer. This transformer, having a ratio of 1:10, will produce a phase voltage of 23,000 volts in each phase of the star-connected secondary. The line voltage, however, will be 23,000 × 1.732, or 39,836 volts.

If we had used either a delta-delta or star-star connection, the line voltage would only be 23,000 with a 1:10 transformer ratio. Knowing that the higher the voltage used on the transmission line the greater will be the economy of transmission and the saving in copper costs, we can readily see the advantage of this connection.

At the receiving end of the line shown at the right, the step-down transformers use the opposite connection, or star-delta, to step the voltage down a maximum amount for a given ratio. Here a 10:1 ratio transformer with star-connected primary and delta-connected secondary will reduce the secondary line voltage to 2300 volts. This voltage can be used directly on large 2300-volt power motors, or it can be stepped down again with smaller banks of 10:1 transformers, using split secondaries to obtain 115 and 230 volts for lighting purposes.

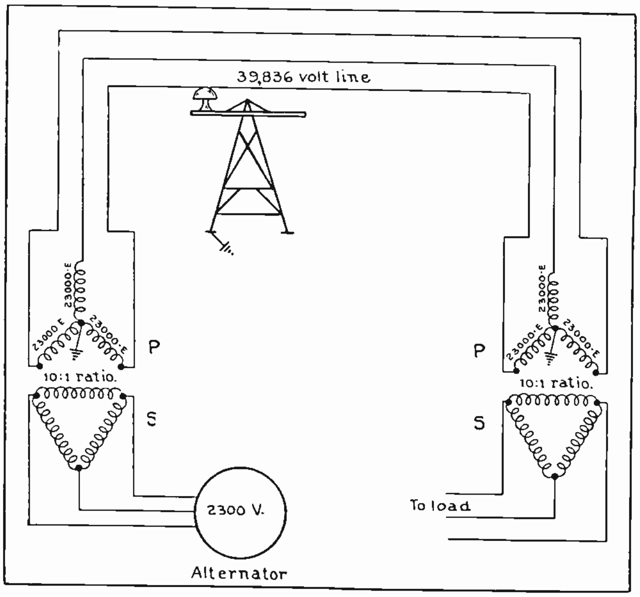

Fig. 130. This diagram illustrates the method and advantage of using star-delta and delta-star transformer connections with transmission lines.

When using transformers with the secondaries connected star and attached to high-voltage transmission lines, the neutral point of the star connection is commonly grounded. This provides another **great advantage for the star connection because it makes possible the use of higher transmission line voltages with less voltage strain between the line wires and ground.**

This greatly reduces the tendency to flash-over the line insulators and makes possible the use of smaller insulators, thereby reducing the cost of the transmission line.

You will note that, while the voltage between the line wires in Fig. 130 is 39,836 volts, the voltage between any line wire and ground or the steel tower supporting the insulator will only be 23,000 volts, or that of one phase winding of the step-up transformer secondary.

This is due to the fact that the neutral point of the star connection is grounded and will always be at approximately the same potential as the tower supporting the insulators.

141. OPEN-DELTA CONNECTIONS

One of the advantages of the delta connection for transformers is that one transformer can be taken out of service for repairs, and service maintained on the remaining two by what is known as the open-delta or V connection.

In other cases where it is desired to provide three-phase service with only two transformers, the open-delta connection is used for permanent installations. The total three-phase capacity of two transformers used in this manner will only be 57.7% of the capacity of three transformers of the same size.

An installation of this type is sometimes made where the average load to be supplied is rather light at the time, but is expected to become heavier as the plant or community expands. When the load increases beyond the capacity of the two transformers, a third one can be added and the connection changed to straight delta. The addition of this third transformer increases the capacity of the group 73% over what it was with the two transformers.

Fig. 131 shows the method of connecting two single-phase transformers in open-delta. The phase voltage in systems connected open-delta will be the same as the line voltages, or the same as with regular delta-delta connections.

The line current will be the same as the phase current, instead of being greater, as with ordinary delta connections. This is due to the fact that line 1 and line 3 have only one path through the phase windings, instead of two paths, as with the straight delta connection.

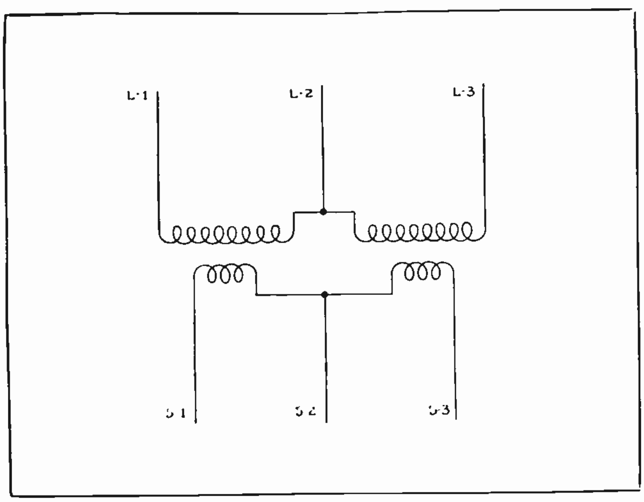

Fig. 131. Connections for using two single-phase transformers to provide three-phase service by what is called the "open-delta" connection.

Where three transformers are connected delta-delta, if one becomes defective it is a very simple matter to connect the remaining two in open-delta. By overloading the transformers to a certain extent, it is possible to maintain nearly full load service for short periods while the defective transformer is being repaired.

Both the primary and secondary of the defective transformer should always be disconnected from the line when changing to open-delta connection with the other two transformers.

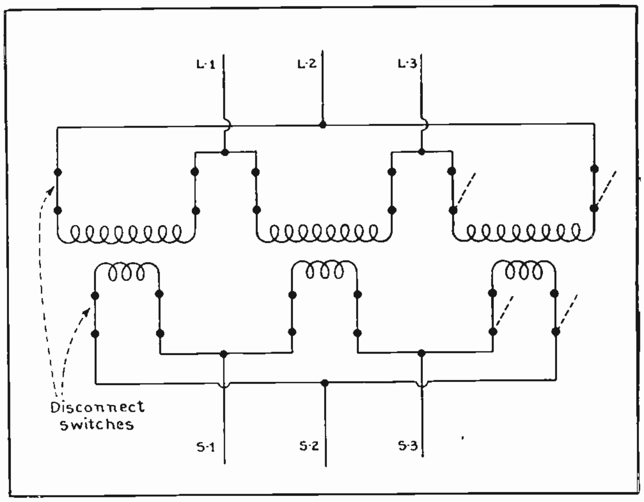

Fig. 132. This diagram shows a convenient method of arranging a bank of transformers with disconnect switches to quickly change over to open-delta operation in case of trouble on one transformer.

It is possible to use the open-delta connection on two of the phase windings of the three-phase transformer, in case one phase becomes defective. If the transformer is of the core type, both the primary and secondary coils of the damaged winding should be left open; but if the transformer has a shell type core, both the primary and secondary windings of the defective phase should be short-circuited upon themselves when the open-delta connection is made on the two good phases.

Fig. 132 shows three single-phase transformers connected delta-delta and equipped with disconnect switches in each of the primary and secondary leads. This arrangement permits a quick change-over to open-delta operation of two transformers if any one should become defective.

For example, if the right-hand transformer should become defective, the disconnect switches could be opened as shown by the dotted lines, and the remaining two transformers would then be operating open-delta. The same change could be made on either of the other two transformers with the same result.

When three transformers are connected either star or delta or in any combination of these except the open-delta, the total kv-a. capacity on the secondary side is equal to three times the capacity of one transformer.

Transformers which are to be connected together in a star or delta on three-phase lines should have similar characteristics; that is, similar kv-a. and voltage ratings, and also similar ratios, impedance, reactance, etc. If the characteristics are not the same the result may be excessive heating of one or more of the transformers or unbalanced line conditions.

142. GROUNDING OF TRANSFORMERS

As previously mentioned, the high-voltage winding of star-connected transformers is frequently grounded at the neutral point, when these transformers are used in connection with transmission lines.

It is quite common practice also to ground the low-voltage secondary windings of step-down transformers connected either star or delta as explained in earlier paragraphs, this protects the low-voltage circuit in case of failure or puncture of the insulation between the high-voltage and low-voltage windings.

It is well to keep in mind that the secondary windings and the circuits to which they are connected are only insulated for the low voltage, and the insulation is not heavy enough to stand the high voltage applied to high-tension primary windings. So, if it were not for the ground on the low-voltage side a flash-over of the high voltage to the low-voltage secondary would tend to puncture the insulation of the low-voltage circuits or some of the devices connected to them.

Having the ground already on the low-voltage circuits provides an easy path for the high voltage to go to ground. This flow of current from the high-voltage winding through the fault to the ground will frequently blow the primary fuses, thus indicating the trouble at once, so that it can be repaired.

The larger sketch on the right in Fig. 133 shows the method of grounding the delta-connected secondary of a three-phase bank of transformers. This ground is commonly made from the center tap, which is taken from the middle of one phase of the secondary winding.

The small sketch on the left in Fig. 133 shows a schematic diagram of the secondary connections and also illustrates the position of the ground.

Assuming that the secondary of these transformers has a voltage of 220 between any two phase wires, the voltage from the various phases to ground will be as follows: A phase to ground, 110 volts; B phase to ground, 190.5 volts; C phase to ground, 110 volts.

The reason for this variation in the voltage between the different phase wires and ground can be noted by careful observation of either of the connection diagrams shown in Fig. 133.

You will note that only half of the center phase winding is between either phase A or phase C and the ground, so there will be only half the voltage

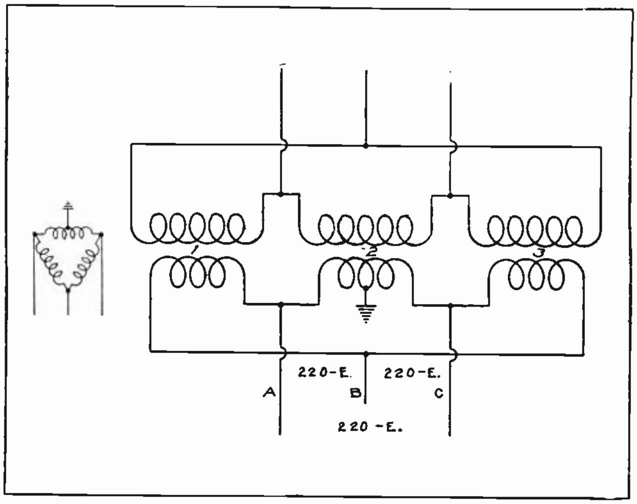

Fig. 133. This sketch shows the method of grounding the secondary circuit of a bank of transformers on which the secondary is connected delta.

of this winding, or 110 volts, between either of these phase wires and ground.

Tracing the circuit from phase B in either direction to ground, we must pass through the secondary winding of transformer No. 1 or No. 3 in series with one-half of the winding of No. 2 to get to ground. This adds the voltages of one whole winding and half a winding, together in series, but 120° out of phase.

To get the effective sum of 220 volts plus 110 volts when these two values are out of phase 120° we add the two voltages and then divide by 1.732, which gives approximately 190.5 volts.

Fig. 134 shows the common method of grounding the low-voltage secondary of a bank of transformers, when the secondary is connected star. The ground connection is made at the common connection, or neutral point, of the three secondary phase windings.

This is illustrated both by the larger sketch at the right and the small schematic diagram at the left in Fig. 134.

If the ground connection were not used on a bank of star-connected transformers, the voltage from any line wire to ground would be the same as the voltage between any two line wires. When the ground is used, the voltage between any line wire and ground is only 57.7 of the voltage between any two line wires, as was previously explained for the high-tension side of transformers which were connected to transmission lines.

This reduces the voltage strain on the insulation of the conductors and devices connected to the secondary circuit and also reduces the shock hazard.

143. PARALLELING THREE-PHASE TRANSFORMERS

When paralleling three-phase transformers the same precautions must be followed as when paralleling three-phase alternators. It is first necessary to phase out the leads and determine like phases.

This can be done by the lamp-bank or motor method explained in the section on A. C. generators.

The two or more transformer banks should be operated from the same primary line. They will then have like frequencies and will operate in synchronism, once they are properly phased out and connected.

When all of the transformer primaries and secondaries are properly marked in the manner previously explained, it is a simple matter to connect leads of like polarity together. If they are not marked, or in any case where the marks are not known to be dependable, the leads should be tested by means of a voltmeter or test lamps, in order to get connected together the leads of like polarities and between which there is no voltage difference.

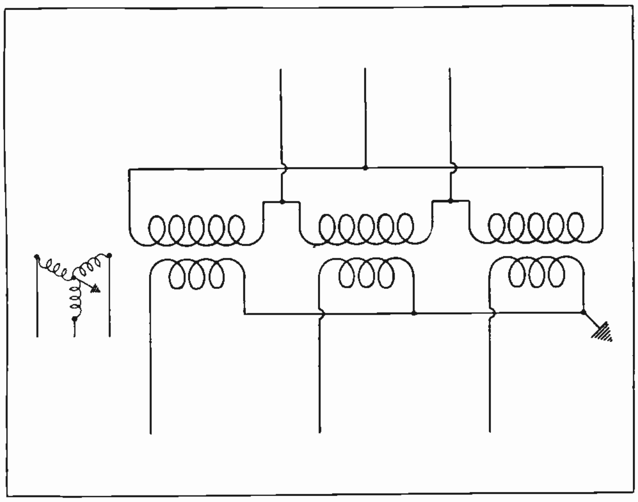

Fig. 134. This sketch shows the location of the ground connection on a bank of transformers with the secondary connected star. Read carefully the explanation of the advantages of this system which are given in the accompanying paragraphs.

144. THREE-PHASE, FOUR-WIRE SYSTEMS

The three-phase, four-wire system is obtained by bringing out the fourth wire from the neutral or grounded point of a star-connected bank of transformers as shown in Fig. 135. This system is used

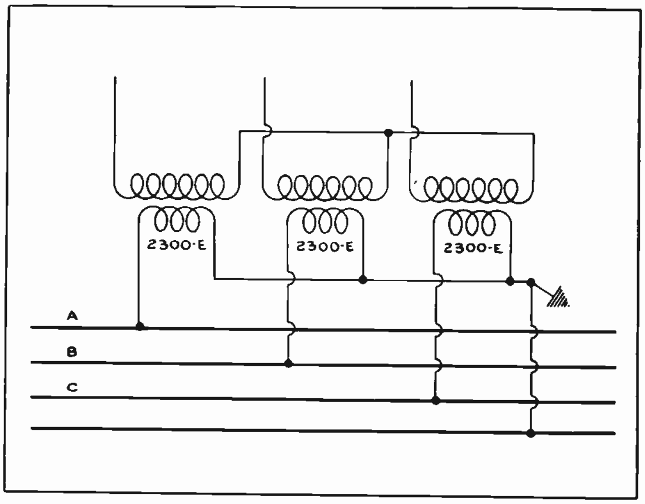

Fig. 135. Connections for three-phase, four-wire service from the star-connected secondaries of a three-phase bank of transformers.

by a great many power companies for distribution circuits of 2300 to 4000 volts which feed power and lighting equipment.

The three-phase, four-wire system provides two different voltages, one of which is obtained between any two of the line wires A, B, and C; and the other between any of the line wires and the neutral wire.

Assuming the secondary phase voltage of the transformers in Fig. 135 to be 2300 volts, the voltage between any two of the line wires A, B, and C will be approximately 4000 volts; while the voltage between any one of the line wires A, B, or C and the neutral wire will be 2300 volts. The voltage from any one of the line wires to ground will be 2300 volts, while the voltage from the neutral wire to ground will be zero.

In any four-wire, three-phase system in which the fourth or neutral wire is taken from the Y point, or common connection of the star-connected transformer windings, the voltage from any line wire to neutral is equal to the voltage between the line wires multiplied by .577, which is the same as dividing by 1.73.

SPECIAL TRANSFORMERS

In addition to the common types of single-phase and polyphase transformers for which the connections were explained in the preceding section, there are several special transformer connections which are frequently encountered in the field.

These special transformers each have certain special applications and are very important in the particular work for which they are designed. You should, therefore, have a good understanding of the principles and uses of the more common types.

145. TAP-CHANGING TRANSFORMERS

It is often desirable to make slight changes in voltage delivered by a bank of step-up or step-down transformers, in order to compensate for varying line drop. In other cases we may wish to change the ratio of the transformer slightly to adapt it to changed operating conditions with other transformers or line equipment.

For this purpose a **Tap-Changing** transformer is frequently used.

Transformers of this type are equipped with extra leads or taps brought out from a certain section of the winding so that, by shifting a sliding connection from one of these taps to the other, the number of turns in the winding can be varied.

This will, of course, vary the ratio between the transformer primary and secondary and will thereby increase or decrease the voltage, according to whether turns are being cut out or added in the winding.

It is usually desirable to be able to accomplish this change without disconnecting a transformer or interrupting service.

There are several different ways of accomplishing this, and one common method is shown in Fig. 136. With this type of transformer, a certain portion of the end of the primary winding is divided into two sections or windings in parallel and marked M and N in the diagram. These sections are equipped with taps and provided with a set of sliding contacts, X and Y, which can be moved from one tap to another. Either of these tapped sections of the transformer winding will carry the entire load for a few seconds without overheating.

The tap switches should not be shifted or changed during the time that load current is flowing through them, or the contacts would be badly burned by the arc set up by the heavy current and high voltage.

To prevent this, an oil switch is provided in each of the parallel circuits or leads to the tapped sections of the winding.

In order to increase the voltage on the secondary we decrease the number of turns on the primary, thereby decreasing the step-down ratio between the two windings.

This is done in the following manner. Oil switch "A" is first opened to temporarily shift all of the load over to the section N of the tapped winding and thereby stop the current flow through section M. The movable contact X is then shifted from stationary contact 3 to 2. Oil switch "A" is then closed, and oil switch "B" opened to shift all of the load to section M.

Movable contact Y is then shifted from stationary contact 3 to 2 in order to balance the number of turns in the two parallel tapped sections. Then oil switch "B" is again closed, allowing the load to divide between the two tapped sections of the winding.

Quite a number of large power transformers are being built with tap changing switches or mechanisms, which are installed either in the top of the transformer case or in an auxiliary box on the side of the transformer.

Some of these tap-changing switches are designed for hand-operation while others are operated by remote control motors or by an automatic voltage-regulating device.

The use of tap changers aids in keeping electric service to customers at the proper voltage and greatly increases the flexibility of transformers equipped with them.

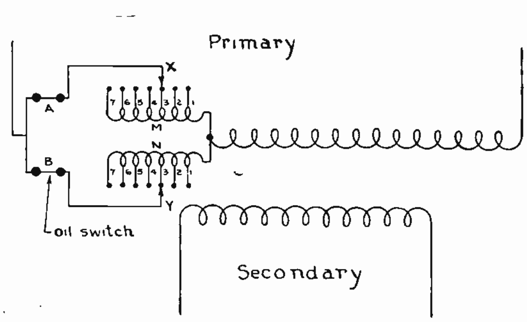

Fig. 136. This diagram shows a method of arranging adjustable connections on the primary of a tap-changing transformer.

146. SCOTT TRANSFORMERS

Sometimes it is desired to change two-phase energy to three-phase, or vice versa. This can, of course, be done with motor-generator sets, but in a number of cases it may only be desired to convert a small amount of power from one system to the other and, therefore, doesn't justify the installation of costly machinery.

In certain older plants which are equipped with two-phase motors, it may be desired to change over to modern three-phase service; or it may be that the power company, in changing over its equipment, can furnish only three-phase service.

In order to prevent scrapping or discarding all of the two-phase motors installed, it is often desirable to change the three-phase energy which is supplied, to two-phase energy to operate a number of the motors, until they are worn out and can be economically replaced with three-phase machines.

This change from three-phase to two-phase or the reverse can be economically made by means of two single-phase transformers, one of which is equipped with a center tap and the other with a tap at 86.6% of its winding.

Two transformers connected in this manner are shown in Fig. 137. This connection is known as the **Scott Transformer** connection and is named after its inventor, Charles F. Scott, former consulting engineer of the Westinghouse Electric and Manufacturing Company.

Two of the three-phase line leads are connected to leads L-1 and L-2 of the single-phase transformer which has the center tap. The third three-phase line lead is connected to the 86.6% tap on the remaining single-phase transformer winding.

The other end of this winding is connected to the center tap of the other unit, as shown in the diagram. When three-phase energy is applied to these three line leads, two-phase energy can be taken from the transformer secondaries at the leads marked "phase A" and "phase B".

On the other hand, if two-phase energy is applied to A and B phase, three-phase energy can be obtained from leads L-1, L-2, and L-3.

The small sketch at the right illustrates this type of transformer with a schematic diagram, and shows the manner in which the three-phase voltages and relations are obtained from the two transformers.

Assuming the voltage of each of the complete transformer windings on the three-phase side to be 100 volts, we find that there will be 50 volts in each of the sections on either side of the 50% tap of the left winding, and 86.6 volts in the active section of the right-hand winding.

Connecting the end of the right-hand winding to the center tap of the left winding causes the voltages in these two windings to be 90° out of phase with each other.

The 86.6% of the right-hand winding is in series with either half of the left winding when tracing from L-3 to L-1 or L-2.

When 86.6 volts are added in series with 50 volts, but are 90° out of phase, the resultant voltage will be 100 volts. So we find that there will be 100 volts between L-1 and L-2, between L-2 and L-3, and also between L-3 and L-1.

Special single-phase transformers can be bought with taps arranged for this connection, or in some cases where it is desirable to change over a small amount of power, two small single-phase transformers can have either their primaries or secondaries rewound and equipped with taps at the middle of one and at 86.6% of the winding of the other.

147. AUTO TRANSFORMERS

The auto transformer is one in which a single tapped coil is used for both the primary and secondary, as shown in Fig. 138-A and B.

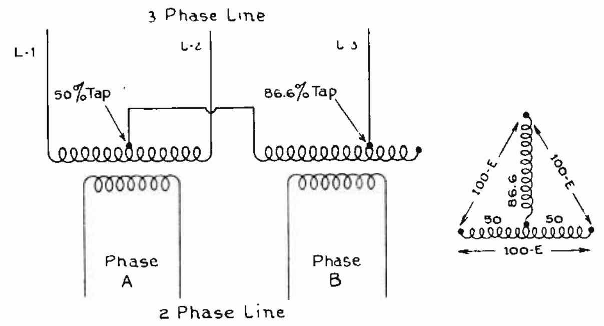

Fig. 137. The Scott transformer connection shown above is often used to change three-phase energy to two-phase or vice versa.

The principal application of auto transformers is for use with starting compensators, to reduce the starting voltage of A. C. induction and synchronous motors.

Auto transformers use somewhat less copper than the regular type of static transformer, but their efficiencies are usually somewhat lower.

The diagram at A in Fig. 138 shows an auto transformer used to step the voltage down, while the diagram at B shows a step-up transformer.

When alternating voltage is applied to the terminals of the full winding in Fig. 138-A there will be a voltage drop across the entire coil, which is equal to the amount of applied voltage.

As the resistance of the coil is very low, the self-induced counter-voltage of the full coil will also be nearly as high as the applied voltage. The induced counter-voltage in the small secondary section of the coil will be proportional to the number of turns included in this section. Therefore, the voltage obtained on the secondary leads will depend upon the point at which the tap, or wire A, is connected to the winding, and the number of turns between wires A and B.

If the secondary section of an auto transformer is wound with heavier wire, a considerably greater current can be taken from this section than is supplied to the primary leads. This is due to the fact that the flux of the upper section of the main coil also cuts across the turns of the lower section, and will thereby induce added energy in this coil.

For starting induction motors this is ideal, because the heavy starting currents which are required can be obtained at low voltage from the secondary of an auto transformer without drawing such a heavy surge of current from the power line.

In the step-up auto transformer in Fig. 138-B, the secondary voltage will be equal to the voltage across the primary coil plus the voltage induced in the secondary section by the flux of the primary coil. In this manner the voltage can be stepped up as much as desired, by properly arranging the ratio of turns in the primary and secondary sections.

Auto transformers are frequently equipped with taps, so that the wire A can be moved back and forth to include more or less turns in the primary or secondary windings.

If wire A in diagram A is moved to a higher point, it will include more turns in the secondary, thereby increasing the secondary voltage of the transformer.

Auto transformers of this type are very convenient for obtaining variable voltages for certain special applications.

Fig. 138-C shows a diagram of an auto transformer connection that can be used to supply 110-volt and 220-volt energy from a 440-volt line, for operation of lights and 220-volt motors. It is also very convenient for obtaining various voltages for test purposes.

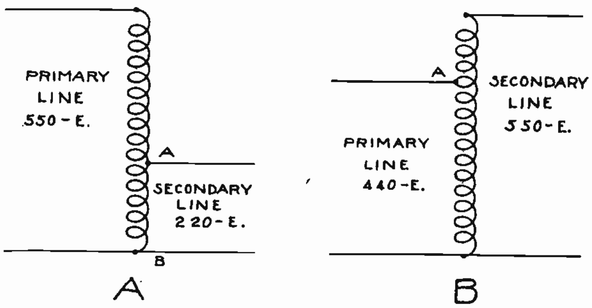

Fig. 138. A shows a step-down auto transformer. Note the reduction obtained in the voltage between the primary and secondary lines. B shows a step-up auto transformer to increase the secondary voltage.

Auto transformers with low ratios such as 2 to 1, are sometimes used on very large installations because of their cost being much lower than that of two-coil transformers. They are not often used however for general light and power service because of the very high voltage to ground which they place on the secondary leads, and the danger that this would create to equipment and persons handling it.

Three-phase auto transformers are used for starting three-phase induction motors, as well as for certain other special applications.

Fig. 139 shows a three-phase auto transformer in which the three ends, one from each coil, are connected together to form a star connection at Y. The other end of each coil is connected to its respective line lead.

A little current will be flowing through the windings of an auto transformer as long as it is connected to the line, the same as the magnetizing current which exists in the primary of any transformer even when no load is on the secondary.

When the secondary of an auto transformer is loaded, the primary current of course increases; but, in the case of a step-down auto transformer such as commonly used with motor starters, if the step-down ratio is 2 to 1, then the primary current will increase only one-half as much as the secondary load current is increased.

Many auto transformers used for motor starters or compensators have their coils equipped with taps, so that the secondary leads to the motor can be changed to obtain higher or lower starting volt-

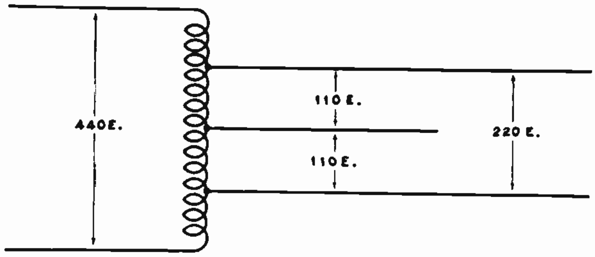

Fig. 138-C. Auto transformer connection for obtaining both 110 and 220 volts from a 440-volt line.

age and thereby increase or decrease the starting torque of the motor.

The diagram in Fig. 139 shows the windings equipped with three taps of this nature. It is quite common to have these taps arranged so that, when the secondary leads are placed on the terminals A, the secondary will deliver 50% of the line voltage to the motor. When the taps are placed on terminal B, the motor will receive 65% of the line voltage. When they are placed on the terminal C, the motor will receive 80% of the full line voltage, etc.

Added diagrams and further explanations of auto transformers will be given in a later section in connection with a A. C. motor controllers.

148. INDUCTION VOLTAGE-REGULATORS

On distribution lines which feed energy to light and power equipment there is practically always a certain amount of load variation as the lights and motors of different buildings are switched on and off.

This variation in the load on the feeder wires also causes a variation in voltage drop on these wires, and a certain amount of variation in the voltage supplied to the load devices.

It is extremely undesirable to have more than a very few per cent. of voltage variation at the load—particularly on circuits which supply current to incandescent lights.

Low voltage causes reduced efficiency of incandescent lamps and reduces the torque and efficiency of motors; and sudden voltage variations cause objectionable flickering of lights. For this reason it is necessary to have some means of automatically regulating the voltage of feeder and distribution circuits which supply energy from the substations to customers' premises.

As the various feeder lines running out from substations usually have different lengths and different

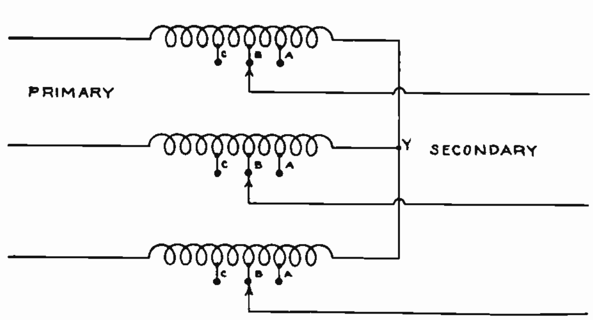

Fig. 139. Three-phase auto transformer in which each winding has several taps so that the secondary voltage can be varied.

amounts of load it is not possible to regulate the voltage of all of these circuits by controlling the voltage at the substation busses. These busses are therefore supplied with one uniform voltage of the proper value to compensate for the ordinary line drop in the feeders and distribution lines.

The voltage of each of the distribution circuits is then automatically regulated to compensate for the load and voltage variations, by means of a device known as an **induction voltage-regulator.**

149. OPERATING PRINCIPLES OF INDUCTION REGULATORS

An induction voltage-regulator is simply a form of transformer which has a movable secondary winding which can be shifted or rotated with respect to the primary winding. The primary winding is called the **stator** and the movable secondary is called the **rotor.**

By turning the secondary winding into various positions with respect to the primary, the voltage induced in the secondary can be varied in amount over a wide range and, by turning the secondary winding far enough, the voltage induced in it can actually be reversed.

In this manner the secondary voltage of the regulator can be made to either aid or oppose the line voltage. Figs. 140-A, B, and C show the connections for an induction voltage regulator.

The primary winding, P, consists of a large number of turns of comparatively small wire and is connected directly across the line. The secondary winding consists of a very few turns of heavy wire which is large enough to carry the entire load current, and this winding is connected in series with the load and one side of the line.

In Fig. 140-A the secondary rotor winding is shown in a position so that it is receiving the maximum induced voltage from the primary, and this voltage is in a direction to add to the primary voltage in series and thereby increase the line voltage.

In this figure, it is assumed that the top wire is positive for the instant, and the arrows near the primary and secondary coils indicate the direction of the voltages in them.

You will recall that when current flows in one direction through the primary winding of an ordinary transformer, it will be flowing in the opposite direction, or 180° out of phase, in the secondary, provided the coils are wound alike.

In Fig. 140-B the secondary rotor is shown turned at somewhat of an angle with the primary winding, and in this position the secondary receives less induced voltage from the primary and therefore doesn't aid or increase the line voltage as much.

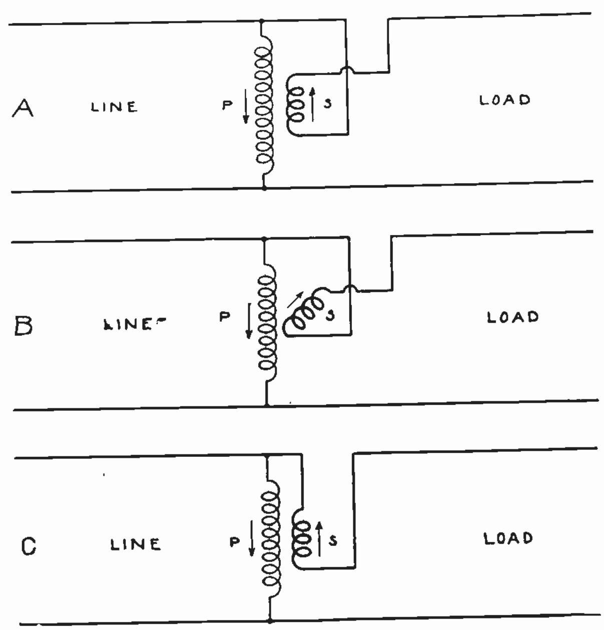

Fig. 140. The above three sketches show the connections and illustrate the principle of an induction voltage regulator. Study carefully each of the three diagrams while reading the explanations given on these pages.

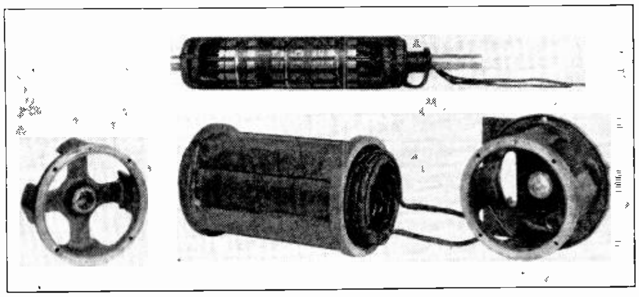

Fig. 141. This photo shows the stationary, primary, and rotating secondary windings of an induction voltage regulator. (Photo Courtesy General Electric Co.)

In Fig. 140-C the secondary has been turned to a position 180° from where it was in A. In this position it is receiving maximum induced voltage from the primary and its voltage is in a direction opposing the primary voltage, so that it reduces the voltage applied to the line.

Fig. 141 shows the stationary primary winding, and also the movable secondary winding which is placed on the rotor. These units are shown removed from the voltage regulator case. This photograph shows very clearly the construction of these elements. Note how the flexible leads of the movable secondary are given a few turns around the shaft of the rotor so that they can be permanently connected in series with the line and yet allow the rotor to make one-half turn, or 180° of rotation. This eliminates the necessity for slip rings and brushes.

150. AUTOMATIC OPERATION OF INDUCTION REGULATORS

The boosting or bucking effect of the induction voltage regulator usually ranges from 5% below normal line-voltage to 5% above line-voltage. These regulators are usually operated automatically by means of small A. C. motors which drive a worm gear and rotate the secondary of the regulator.

The motor is controlled or started, stopped, and reversed by a set of potential relays or contact-making voltmeters with auxiliary contacts on the movable element.

When the voltage on the distribution line drops below normal, the relays close the circuits of the

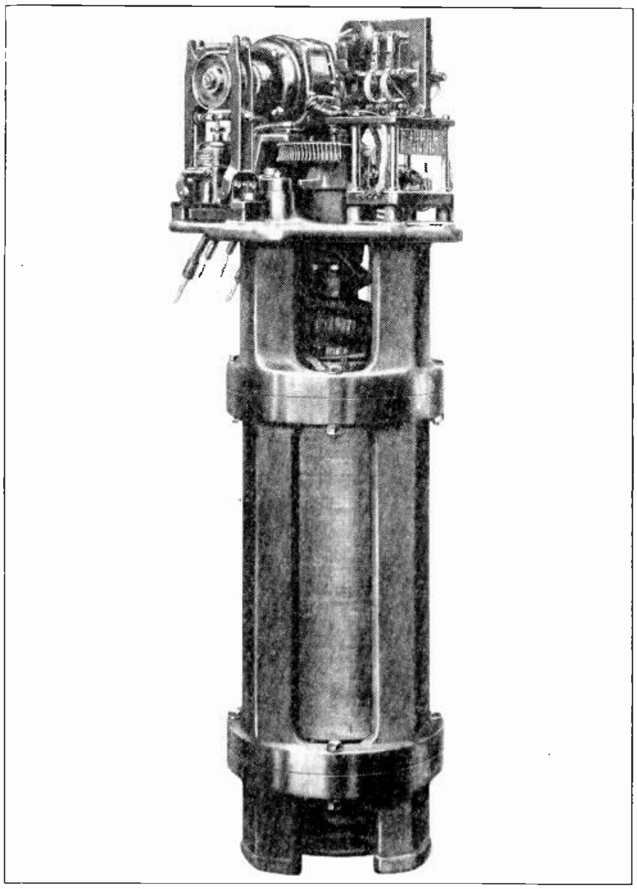

Fig. 142. Complete stator and rotor of a single-phase voltage regulator with the operating motor attached. (Photo Courtesy General Electric Co.)

motor to revolve the secondary winding of the regulator to a position where it will receive a greater induced voltage of a direction to aid and increase the line voltage. If the line voltage rises too high because of removal of practically all the load from the line, the relay contacts close another circuit to reverse the motor and rotate the secondary winding of the regulator to bucking position, where its voltage will oppose that of the line.

Fig. 142 shows a completely assembled primary and secondary unit of an induction regulator. The operating motor and part of the contacts are shown attached to the top of the stator frame in this view.

Fig. 143 shows a complete single-phase regulator with the primary and secondary enclosed in a tank of insulating oil. The sensitive voltage relay, adjustable tap-control, and resistance box and switch are shown mounted on a panel on the front of the regulator.

Induction regulators are also made for three-phase operation. These are wound similarly to the stator of the three-phase induction motor. Regulators of the induction type are in very common use in modern substations which supply alternating current to feeder and distribution circuits. Therefore, it will be well worth your while to obtain a thorough understanding of the principles of this device and to carefully observe and study the various parts of the control and operating mechanism of the regulator in your A. C. shop Department.

151. INSTRUMENT TRANSFORMERS

While on the subject of transformers, it will be well to consider more fully the principles and construction of instrument transformers which are used in connection with meters on high-voltage A. C. circuits.

The use of these transformers has already been explained to some extent in the section on Alternating Current Meters. Those which are used to reduce the current of heavy-duty power circuits and to operate ammeters and the current elements of wattmeters and watthour meters, trip coils of oil switches, operating coils of current relays, etc., are known as **current transformers (C.T.)**

The other type, which are used to reduce the voltage of high-tension circuits and to operate voltmeters, potential elements of wattmeters and watthour meters; power-factor meters, synchroscopes, potential relays, etc., are known as **potential transformers (P.T.)**

Instrument transformers are carefully and specially designed to give very accurate ratios of transformation on voltage and current values within the range of which they are designed.

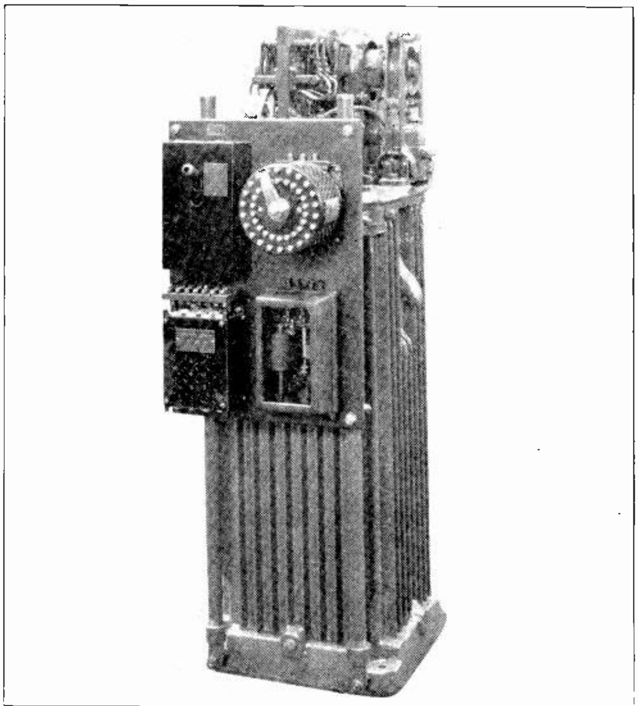

Fig. 143. This photo shows a single-phase regulator enclosed in its tank and equipped with the operating motor and control relays. (Photo Courtesy General Electric Co.)

152. CURRENT TRANSFORMERS

The primary of a current transformer is always connected in series with the line of which the current is to be measured, as shown in Fig. 144-A. This primary winding usually consists of only one or two turns and in some cases of just a straight conductor passed through the core around which the secondary is wound. This produces the same effect and ratio as one loop or turn.

On circuits carrying very heavy currents, the flux set up by one turn, or even just a short section of the straight conductor, is sufficient to induce the proper voltage in the secondary winding, as the instruments require very little power to operate their moving elements.

The secondary winding consists of a great many turns and its terminals are connected directly to the terminals of the ammeter, wattmeter, or relay which the transformer is to operate.

The secondary of the current transformer should always be grounded for safety in case of a breakdown of the insulation, which might allow the high voltage of the line to get to the low-voltage circuit.

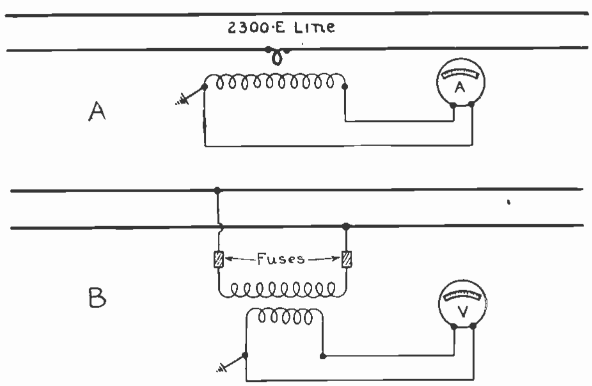

Fig. 144. A shows the connections for a current transformer which is used to operate A. C. ammeters, wattmeters, and current relays. B. Connections for potential transformer used to operate voltmeters, potential elements of wattmeters, potential relays, etc.

Fig. 145 shows a current transformer which is designed for connecting in series with power cables or lines. The cables are connected to the leads of the heavy primary conductor by the copper lugs and bolts shown attached. The leads to the instrument are taken from the two small terminals on the connection block on the lower left of the transformer core.

Fig. 145-A shows a current transformer which is designed for connection in series with a bus bar on a switchboard.

153. CAUTION

As previously mentioned in the lesson on A. C. Meters, the current transformer which has its primary connected in a live line **should never be left with its secondary open-circuited.**

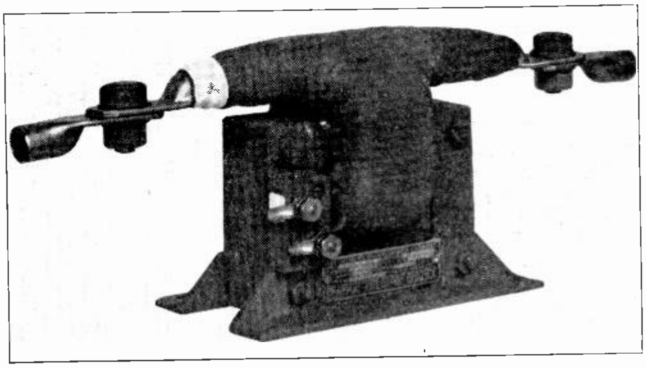

Fig. 145. This photo shows a common type of current transformer for use with cable lines or small bus bars.

Before disconnecting the meter leads or relay leads from the secondary of the current transformer, **the transformer secondary should be short-circuited with a good, secure connection.** If this is not done, when the instrument is removed there will be a dangerously high voltage built up in the secondary winding of the transformer. This high voltage may puncture the insulation of the transformer secondary winding, or of the meter just as it is being disconnected or reconnected; or it may cause a serious shock to the operator who is making or breaking the connections.

You will note by observation of the diagram in Fig. 144-A that, with one turn in the primary and a considerable number of turns in the secondary, a current transformer resembles a step-up transformer with the secondary as the high-voltage winding. It would act as such if it were not for the fact that the meters and devices connected to the secondary are of very low resistance, and the current which normally flows through the secondary sets up a flux that opposes the primary flux, and thereby limits the amount of induced voltage to a very low value.

This principle was explained in Article 125.

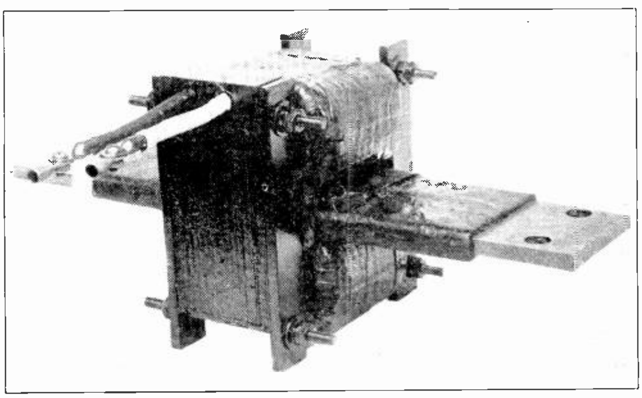

Fig. 145-A. Bus-bar type current transformer for use with large bus bars on switchboards. (Photo Courtesy General Electric Co.)

The short-circuit should always be left on the secondary winding until after the meters or devices have been reconnected to it. This short-circuit will not cause the secondary winding to become damaged or burned by overload because the increased current which tends to flow through the secondary winding, when shorted, immediately sets up a heavy flux that more completely neutralizes the flux of the primary and thereby allows very little voltage to be induced in the secondary as long as its circuit is closed.

If this circuit were left open, however, there would be no current flowing and no secondary flux to oppose the primary field, and this would allow the primary flux to build up to full normal value and induce in the secondary the very high voltage which has been mentioned.

154. POLARITY MARKINGS AND RATIOS

The polarity of current transformers is usually indicated by permanent white markings placed on the primary and secondary leads.

The relative instantaneous directions of the current will be **into the marked primary lead,** and **out of the marked secondary lead.**

Current transformers ratios can be expressed in different ways. One common method is as follows: 80:5, 400:5, 250:5, etc.

These respective indications or markings mean that the maximum secondary rating is 5 amperes when the primary is fully loaded by the number of amperes expressed by the first figure of the rating. In other words, transformers are designed with the various proper ratios so that 80 amperes through the primary will produce a low of 5 amperes in the

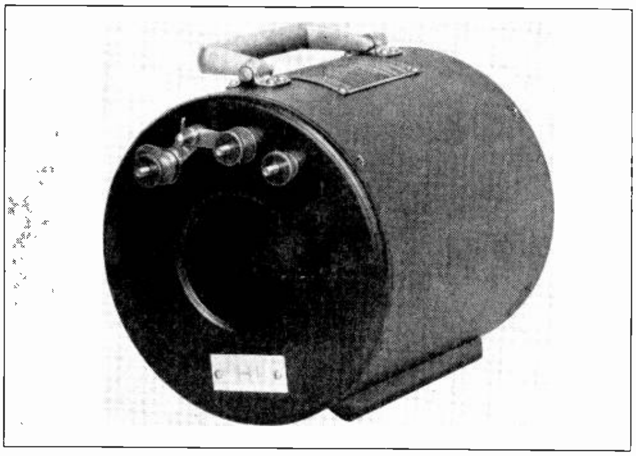

Fig. 146. Portable current transformers of this type are very convenient when making tests on lines or electric machines with portable ammeters and wattmeters. (Photo Courtesy General Electric Co.)

secondary; or, in the case of another transformer, 400 amperes flowing through the primary will produce a flow of 5 amperes through the secondary, etc.

With current transformers of this type it is possible to use ammeters which have windings with a maximum capacity of 5 amperes. The ammeter scale is then calibrated according to the ratio of the transformer so that the meter will indicate the full line current rather than the amount of current actually passing through the meter coil itself.

Another method of expressing current transformer ratios, is as follows: 80:1, 600:1, 1200:1, etc.

The principle involved in this method is the same as that of the transformer ratios previously explained; and ammeters of 5 ampere maximum capacity are used and have the scales calibrated according to the transformer ratio.

155. ADVANTAGES AND APPLICATIONS OF CURRENT TRANSFORMERS

Ammeters for use without current transformers and designed for a flow of more than 100 amperes through their coils, are usually not very accurate and require very heavy and bulky coils to carry the current.

As many alternating current power circuits carry loads of several thousand amperes, current transformers are very commonly used. They serve the same general purpose as ammeter shunts do in direct current circuits, even though the transformers operate on a principle of induced voltage entirely different from that of voltage drop due to resistance in the shunts.

Fig. 146 shows a portable current transformer which can be conveniently used with portable ammeters or wattmeters for making tests on heavy power circuits. This transformer is so constructed that the cable or line on which the current is to be measured can be passed through the hole in the center of the transformer core. The flux around the line conductor is sufficient to operate the transformer secondary and instruments attached.

In cases where the voltage of the line on which the current is to be measured exceeds 500 volts and possibly ranges up into the thousands of volts, it is much safer to use current transformers to operate meters and relays. By using a transformer, the windings of the ammeters or relays are kept insulated from the line voltage. Some power companies make it a general practice to use current transformers on all lines of 220 volts and over.

There is often a tendency on the part of operators and electrical men in the field to overload current transformers by connecting too many instruments on one transformer. This is not good practice, as it causes inaccurate meter readings, particularly where the current elements of wattmeters are connected to the same transformer with ammeters.

Most meters are matched and calibrated to operate with certain current transformers and for accurate readings these should be kept together.

Other types of current transformers are designed to operate overload trip-coils, relays, etc., and these should not be used with ammeters or wattmeters.

156. POTENTIAL TRANSFORMERS

A potential transformer resembles an ordinary single-phase power transformer, except that it is of only a few watts capacity. The primary windings of potential transformers consist of a great number of turns, and are connected across the high voltage lines and protected with special fuses known as potential transformer fuses.

The secondaries are commonly wound for 100 or 110 volts. Fig. 144-B shows the connections for a potential transformer, and the voltmeter properly connected to its secondary. The secondaries of these transformers are also grounded for safety reasons and to immediately ground the high voltage in case of failure of the insulation between the primary and secondary windings.

Voltmeters and the potential elements of wattmeters which are designed for use with potential transformers are found and constructed the same as voltmeters for lines of 100 or 110 volts, and their scales are calibrated according to the ratio of the potential transformer, so the meters will indicate the full line voltage.

It is quite general practice to use potential transformers for the operation of voltmeters, wattmeters, and potential relays on lines of 200 volts and over.

It is very seldom advisable or practical to use voltmeters directly connected to lines of over 600 volts.

On the left in Fig. 147 is shown a potential transformer for a primary voltage of 220 volts. The terminal markings, H-1 on the primary and X-1 on the secondary, can be seen in this photo.

The view on the right in this figure shows a large oil-insulated current transformer for use with a line of 25,000 volts. The in-going and out-going leads to the primary are both carried through the large porcelain insulating bushing. One lead is in the form of a small rod which goes down through the center of the bushing, and the other lead is in the form of a metal sleeve which surrounds the inner rod but is well insulated from it.

Potential transformers for use on very high voltage lines are also built with their windings immersed in tanks of oil and have two high-voltage insulating bushings for their primary leads, which are connected across the line.

Oil-insulated instrument transformers of this type are commonly installed outdoors in the substation structure where the high voltage lines enter or leave the station.

157. TRANSFORMER TESTS

Three very common tests which you may often be called upon to make on transformers are those for determining the **core loss, copper loss,** and the **regulation** of various power transformers.

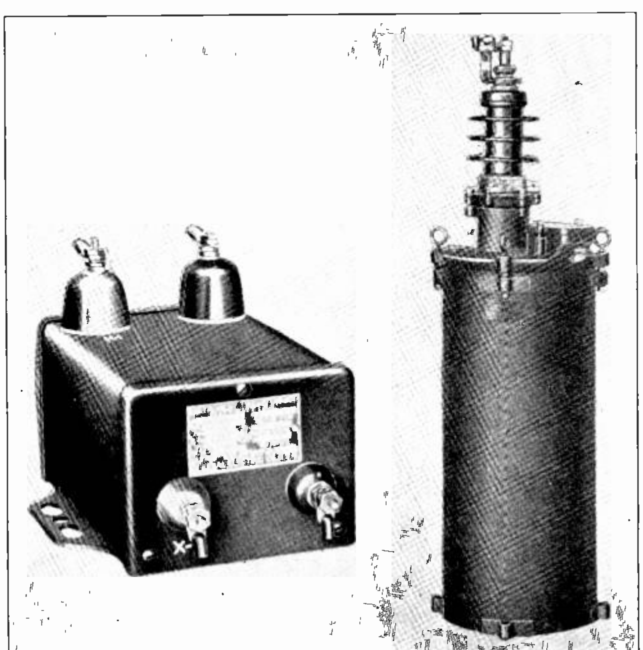

Fig. 147. At the left is shown a small potential transformer with the high-voltage terminals on the top and the low-voltage terminals on the end. Note the polarity markings on the case. On the right is shown a large oil-insulated power-type current transformer.

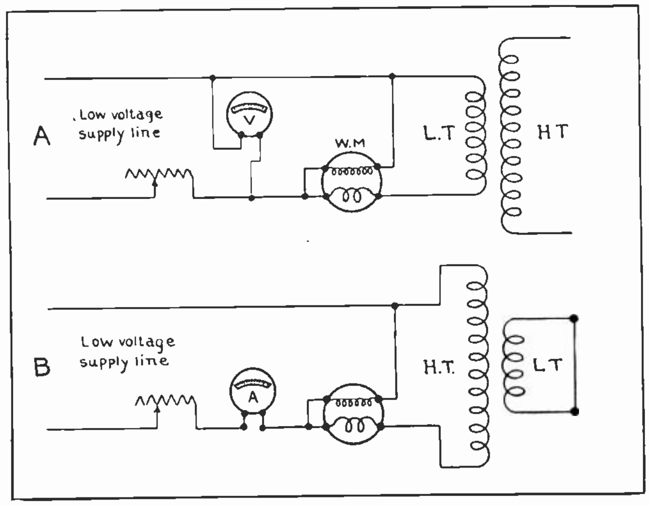

Fig. 148. A shows the method of connecting a voltmeter and ammeter to a transformer to make a core loss test. B shows the connections for making a copper loss test.

These losses and figures on the characteristics of the transformer can usually be obtained from the manufacturers, but the tests for determining them are very simple and are often performed in the field.

The connections for making the core-loss test are shown in Fig. 148-A. When performing this test it is generally more convenient to use the low-tension winding for applying the power, thus avoiding unnecessarily high voltage on the instruments.

For making the core-loss test, the wattmeter and voltmeter of the proper ratings and some form of rheostat are required, and they should be connected as shown in the diagram. The secondary of the transformer should be left open-circuited during the test. The rheostat should be adjusted until normal voltage is applied to the primary winding, and the wattmeter reading will then indicate the core loss of the transformer in watts.

In other words, **when the secondary of the transformer is open and not loaded, the energy required to magnetize the core will be the core loss.** As previously mentioned, the core loss of a transformer is practically the same at no load as at full load.

The connections for making the copper-loss test are shown in Fig. 148-B. In this test it is usually more convenient to use the high-voltage winding of the transformer as the primary to be excited. The low-voltage secondary should be short-circuited during the test.

A low voltage is then applied to the high-tension coil and the rheostat is adjusted until the ammeter indicates that the current flow is equal to the full load current rating of the high-tension winding. When this current value is reached, the wattmeter reading will indicate the full-load copper-loss.

With the secondary short-circuited in this manner it is usually necessary to apply only 1 to 3 per cent. of the rated high-tension voltage to bring the current up to full-load value for the high-tension winding.

The regulation of a transformer may be determined approximately by the following method.

First, measure the secondary voltage under full load, with the transformer primary supplied with rated voltage and frequency. When the secondary load is removed, the voltage will rise and the amount of increase should be noted.

This increase, or difference between the full load and no load voltage, divided by the full load secondary voltage will give the per cent. of regulation.

158. FIELD PROBLEMS

In each of the following problems except the last one, the answers are given; but you should carefully work them out, and also make in each case a connection diagram of the equipment mentioned, or that which would be required, just as you would connect it up right on the job.

Suppose that you were to install a bank of three single-base transformers to supply current to a motor load of 150 h. p. What size transformers would you install?

It is considered good practice to install about 1 kv-a. of transformer capacity per h. p. of secondary load. This will allow for the loss in the transformers and motors and also for the power factor, which is usually somewhat below unity on a system loaded with motors.

So, as the exact power factor and current ratings of the motors in this case are not known, we should install transformers with a total three-phase capacity of 150 kv-a.

When 150 kv-a. is divided among three single-phase transformers, it will require transformers of 50 kv-a. each.

In another case, suppose you wish to determine the amount of current that can be taken from each secondary line wire of a three-phase bank of transformers which have a total capacity of 600 kv-a. and a secondary voltage of 440 volts.

We know that the apparent watts divided by (volts $\times$ 1.732) will give the line current on any line wire of the three-phase system.

Then, as apparent watts are equal to 600 kv-a. $\times$ 1000, or 600,000 watts, the current will be found in the following manner:

$$I = \frac{600{,}000}{440 \times 1.732}, \text{ or 787 amperes per line conductor.}$$

If on some future job you have a bank or transformers with a step-down ratio of 2:1, with the primary windings connected star to a 440-volt circuit and the secondary windings connected delta, what voltage will be obtained from the secondary line leads?

This problem can be solved in the following manner:

If the transformer primaries are connected star to a 440-volt line, the voltage across each of the primary phase windings will be:

$440 \div 1.732$, or approximately 254 volts.

Then, if the transformer step-down ratio is 2:1, the voltage across the secondary phase windings will be:

$254 \div 2$, or 127 volts.

As the secondary windings are connected delta, the line voltage will be the same as the phase winding voltage, or 127 volts.

If an alternator supplying 6000 volts is connected to the primary of a delta-star bank of step-up transformers which have a ratio of 1:11.55, what will

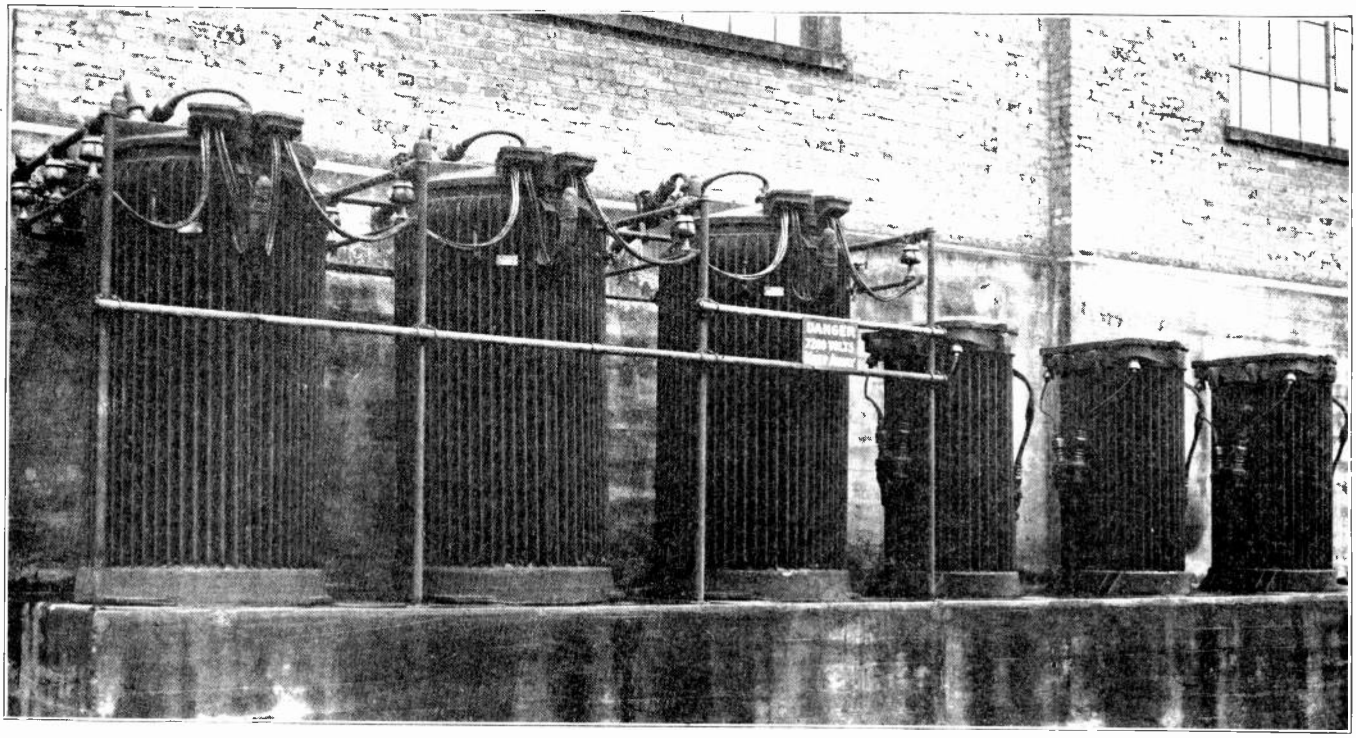

Fig. 149. This photo shows two three-phase banks of transformers of different sizes. Note the manner in which the connections are made. Connections from transformer banks are very frequently run through conduit or lead-covered cables to the circuits they are to supply. In some cases connections are made to rigidly supported bus bars which may lead to a switchboard or switching station.

be the high-tension line voltage obtained from the star-connected secondaries of the transformers?

This problem can be solved in the following manner:

If 6600 volts are applied to the delta-connected primaries of the transformers, then the voltages across each of the primary phase windings will be 6600. With a step-up ratio of 1:11.55 the voltage across each of the phase windings on the secondaries of the transformers will be 76,230 volts.

Then, if these secondaries are connected star, the line voltage will be 76,230 × 1.732, or 132,030 volts.

This same line voltage can be obtained with a bank of transformers connected in this manner and having an even ratio of 1:10, by simply increasing the alternator voltage from 6600 to a little over 7622 volts.

Which transformer connections could be used to raise the voltage of a 13,200-volt alternator to 132,000 volts for the transmission line, if the bank of transformers has a step-up ratio of 1:10?

159. MAINTENANCE AND CARE OF TRANSFORMERS

Transformers usually require considerably less maintenance than most other electrical machines; because transformers have no moving or wearing parts, such as bearings, etc.

There are, however, certain important features which should not be overlooked when installing new transformers and also in the regular inspection and care of these devices, to make certain that they are operating under proper conditions.

When installing transformers they should whenever possible be placed in a location where there is plenty of free circulation of fresh air to carry away the heat developed in the transformers.

Transformers are quite often installed in special rooms, known as **transformer vaults**, inside of various buildings. These rooms should be well provided with openings for ventilation, and in many cases it is advisable to have some sort of fan or blower system to constantly circulate fresh air through the transformer vaults.

Where transformers have water-cooling coils in the tanks, the circulation of air around the tanks is not so important; but, even with these types of transformers, a great deal of the heat will be carried away and their operating temperature kept lower if plenty of fresh air can come in contact with the tanks.

When transformers are installed out-of-doors, the air problem will usually take care of itself; but, if the transformers are equipped with water-cooling coils, they should be inspected frequently to see that the circulating water supply is not interrupted by failure of the pumps, and also to see that this water as well as the transformer itself are kept at the proper temperature.

In certain cases where transformers may be temporarily overloaded to maintain service during emergencies, or where conditions make their cool-

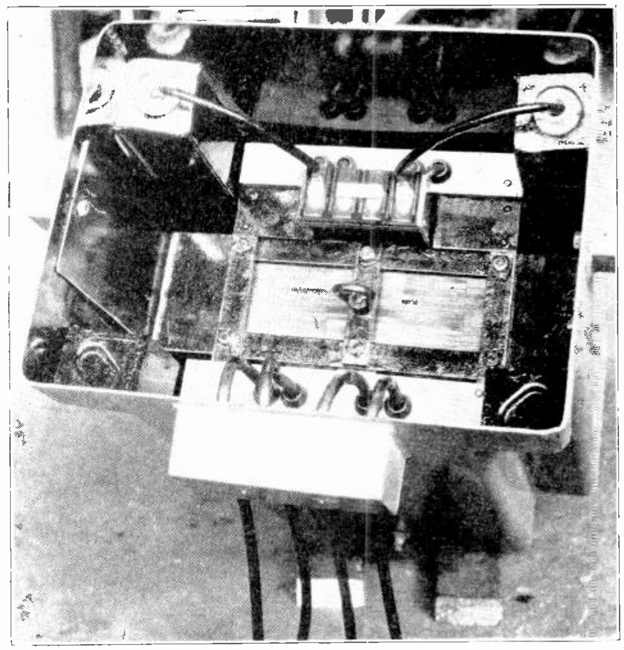

Fig. 150. This photo shows the inside of a small distribution transformer with the oil removed. Many transformers of this type are provided with a terminal block mounted on the core inside of the tank so that the connections can be changed to obtain different voltages.

ing difficult, they may be kept at safe temperatures by means of fans or blowers to direct air against their tanks or radiators. Sometimes a spray of water against the tanks from a set of perforated pipes will greatly aid in cooling them. The water should, of course, be kept away from high voltage lead-in wires and bushings.

As previously mentioned, most large transformers are provided with thermometers to indicate the temperature; and for highest operating efficiency, as well as for safety of the insulation of the windings, the temperature should be kept at or below the maximum rating which is usually marked on the transformer name-plate.

160. DRYING OUT TRANSFORMERS

When installing new transformers which have been shipped without the oil in the tanks, or used transformers which have become damp, it is very important to see that the windings and tanks are thoroughly dried out before the oil is placed in the transformers.

This is usually accomplished with some form of air heater and fan arrangement for blowing dry, heated air through the windings. Large transformers may require several days to thoroughly dry out.

In emergency cases the windings may be heated to dry them out by short-circuiting the secondary winding and applying from 1 to 2 per cent. of the normal rated voltage to the primary.

A rheostat is generally used in series with the primary winding to avoid too rapid temperature rises, and the actual drying temperatrue should not be reached for several hours after starting to apply the low voltage to the primary.

This method of drying out a transformer must be performed with great care at the start or the inner sections of the winding may reach dangerously high temperatures before the outside sections become warmed up.

The principal reasons for drying out transformers so carefully are both to prevent moisture from reducing the dielectrical strength of the insulation on the windings and to prevent any of this moisture from being absorbed by the oil when it is placed in the transformer tank.

The degree of dryness obtained can be determined by measuring the insulation resistance between the winding and core with a megger.

161. EFFECT OF WATER ON TRANSFORMER OIL

The presence of even a very slight amount of water in the oil will greatly reduce its dielectric strength or insulating qualities. The dielectric strength of good transformer oil is usually between 220 and 250 volts per mil. In other words, it will require a voltage of this amount to puncture or break through 1/1000 of an inch of good transformer oil.

The common test for transformer oil is made by placing a sample of the oil in a testing cup or receptacle in which is submerged a pair of round test electrodes one inch in diameter, and with flat faces spaced 1/10 of an inch apart.

When high voltage from a test transformer is applied to these terminals of the test gap, the 1/10 inch layer of oil between them should stand a potential of about 22,000 volts before breaking down. If the oil flashes through at a much lower voltage than this, it indicates the presence of moisture or dirt in the oil.

If oil which has almost no water in it, or we will say not over 1/10 part of water in 10,000 parts of oil by volume, has a breakdown voltage of over 20,000 volts, when water is added to the extent of one part of water in 10,000 parts of oil, the oil will usually break down at less than 10,000 volts; showing that its dielectric strength has been reduced more than one-half by even this very small moisture content.

Only a good grade of mineral oil should be used in transformers. The principal requirements are that such oil should be free from moisture, dust, dirt, and sediment. It should also be free from acid, alkali, and sulphur. It should have a low flash point, and should have the previously mentioned dielectric strength of about 220 volts per mil.

During normal operation of the transformer it is quite probable that the oil will absorb more or less moisture from the atmosphere.

Most transformer manufacturers equip their transformers with air-tight or water-tight insulating bushings around the conductors or leads where they leave the tank, and also with moisture seals under the tank covers. In spite of this, a certain amount of moisture may enter the tank by the "breathing" action which is due to expansion and contraction of the oil with changes of temperature in the transformer, and which causes air to be forced in and out of the transformer tank with these changes in temperature.

Even when transformers are equipped with the air-dryer or moisture-absorbing units in the breather or ventilator previously explained, some moisture may gradually be absorbed by the oil.

The presence of this moisture may not be visible to the eye when the oil is examined, but it can be detected by the voltage-breakdown test.

If a pint of oil and a pint of water are vigorously shaken together in a container and then allowed to stand for a few minutes they will separate because oil is the lighter of the two. Most of the water will settle to the bottom, but a certain number of very small particles of water will be retained in suspension in the oil.

The same condition is met in the case of transformers. Most of the first moisture which enters the tank remains suspended in the oil until the oil can hold no more water, and then the water begins to settle to the bottom of the tank.

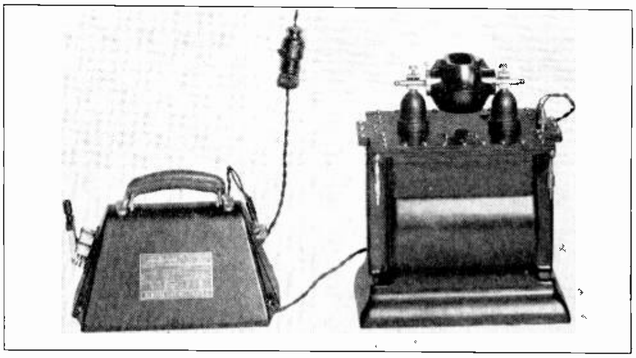

Fig. 151. Portable oil testing outfit consisting of high voltage transformer oil test cup and voltage adjuster. (Photo Courtesy General Electric Co.)

162. TESTING TRANSFORMER OIL

We should never wait for water to appear at the bottom of the tank; but, instead, the oil should be periodically tested by removing small samples from the drain valve at the bottom of the tank and testing these samples in a high-voltage test gap such as previously described.

If, at any time, the oil removed from the bottom of the tank breaks down at voltages below 16,500 on a standard test gap, the oil should be both dried out and cleaned. If this is neglected it may result in the dielectric strength of the oil becoming so low that it will cause a flash-over between the transformer windings and result in serious damage.

Fig. 151 shows a convenient portable oil-testing device which consists of a small high-voltage transformer capable of producing secondary voltages of from 15,000 to 25,000 volts. The oil test cup or receptacle is mounted above the transformer and is attached to the high-voltage terminals. The oil cup is made of an insulating composition and has the metal electrodes inside the cup with their shafts extending through the ends to the transformer terminals.

One of the electrodes is adjustable so that the cup can be accurately set for various tests. There is also provided a voltage adjustment knob, located between the electrode posts. The power required by a test outfit of this kind is so small that it can be operated directly from an ordinary 110-volt lighting circuit.

When testing oil with such a test outfit, the cup is usually filled so that the oil is about an inch above the electrodes, and after allowing sufficient time for the oil to flow between the gap faces and for all bubbles to rise to the top, the voltage is applied, low at first, and gradually increased until the sample breaks down. Several samples are usually tested to obtain average results and avoid mistakes.

163. CLEANING TRANSFORMER OIL

There are three common methods or removing moisture and dirt from transformer oil. These methods are boiling, filtering, and the use of centrifugal separators.

The first method is the least used of the three and is generally only resorted to in emergencies.

Oil **filter presses** are quite commonly used by a number of plants and power companies, and the **centrifugal separator** is very extensively used where large amounts of oil must be cleaned frequently.

To dry the moisture out of oil by boiling is a somewhat crude method but it may occasionally be handy in emergencies. To do this, it is only necessary to heat the oil to a temperature slightly above the boiling point of water, or 212° F. Maintaining the oil at this temperature will gradually boil out the water.

The temperature of the oil should not be raised more than about 20° above the boiling point of water, or the excessive heat may injure the quality of the oil and lower its dielectric strength.

Oil filtering is accomplished by forcing the oil through a series of filter papers. These filter papers are similar to blotting papers. A number of them are held securely clamped in a special press, such as shown in Fig. 152; and oil is forced through these filter papers one after another, by means of an electrically-driven pump.

The filter papers will allow the oil to pass slowly through them, but will stop and hold most of the moisture. They will also stop most of the dirt and sediment which the oil may contain.

A pressure gauge is connected in the oil-circulating system between the pump and the filter press, so that the proper pressure may be maintained on the filter papers. After the pump has been started a few minutes, the pressure should be noted. If at any time during operation the gauge indicates a sudden pressure drop, the pump should be immediately shut down, because the reduced pressure is usually due to some of the filter sheets having been punctured by water.

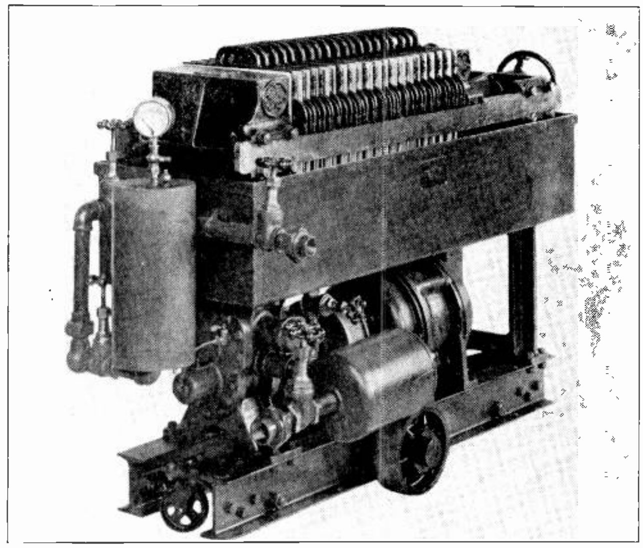

Fig. 152. This photo shows a filter press for cleaning and removing the moisture from insulating oil. Note the motor-driven pump mounted underneath the filter press. (Photo Courtesy General Electric Co.)

It is then necessary to drain the oil from the filter and replace the punctured sheets as well as several adjacent sheets on each side of them. This is done in order to guard against missing a few sheets which have very small punctures that may not be easily seen.

The moisture-laden oil which is drained from the filter each time it is shut down, should be set aside and filtered at the end of the run. This will eliminate a lot of unnecessary shut downs, as a considerable amount of the water may have settled out of the bad oil during the time it was left standing.

Centrifugal oil separators such as the one shown in Fig. 153 separate the oil and water by whirling them at high speed, causing the two to leave the separator disks at different levels because of the different weights or specific gravities of oil and water.

This method is very rapid, convenient, and clean, and is very commonly used in large power plants and by power companies which have to clean large amounts of insulating oil from transformers, oil switches, etc.

Large transformers are usually provided with oil drain connections at the bottom of the tank and refilling connections at the top. It is not necessary to take a transformer out of service in order to clean the oil, as connections can be made to both the bottom and top of the tank; so that the oil can be run through the filter press or centrifugal separator and the clean oil returned to the top of the tank as fast as the dirty oil is withdrawn from the bottom.

By this method some of the oil may, of course, be run through the cleaning process several times; but, as soon as the sufficient moisture and dirt have been removed so that a test sample of the oil in the transformer rests up to the proper voltage again, the cleaning process can be stopped and the filter or separator disconnected from the transformer.

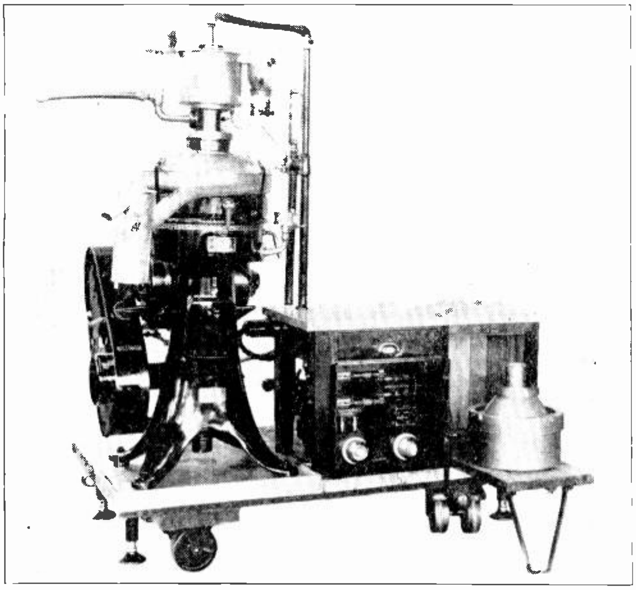

Fig. 153. Motor-operated centrifugal oil purifier which separates water and dirt from the oil by revolving them at high speeds. (Photo Courtesy General Electric Co.)

Sometimes it is necessary to take a transformer out of service and thoroughly clean the tank and windings to remove all sediment and dirt from the bottom of the tank and also any accumulations of dirt or oil sludge which may be clinging to the windings and clogging up the oil circulation spaces, thus preventing proper cooling and causing the transformer to overheat.

There are many thousands of small and large transformers in use in power plants, substations, and industrial plants today; and it is because you will undoubtedly have frequent occasion to use a good working knowledge of these devices that their operating principles, connections, and care have been quite thoroughly covered in this section.

This subject is of sufficient importance so that you should make sure that you have a thorough understanding of the material covered in this section. You should also be very thorough in making the various important tests and connections on the transformers in the A. C. Shop Department of your course.

TRANSFORMER DESIGN DATA

We have found that transformers are made in many different sizes and types, and for almost any purpose or need. Very often the alert electrician can think of profitable uses for transformers other than the uses in which they are commonly found.

In some cases, one may have a need for a special transformer which is not available or which may be too costly to buy for the particular purpose, and you may desire to build a unit from available core iron, and wire, which may have been salvaged from some other transformer. Or you can purchase core iron cut to specifications from various steel companies, and magnet wire from electrical supply houses, for building special transformers.

The design of large power transformers for maximum efficiency and power factor is a job for technically trained engineers, and it is not our purpose to go into such details or mathematical problems. However, it is not a very difficult matter for the practically trained electrician to build a simple transformer of small or medium size, which may be very satisfactory for some certain job or requirement. The following convenient transformer construction data is provided for this purpose.

Before starting to design or construct any transformer, it will be well for us to have well in mind just what a transformer is, or what are its essential parts such as the core, the primary winding, the secondary winding, and the necessary insulation. The core, consisting of thin iron strips or laminations must be large enough to carry the required magnetic flux without saturation or too heavy losses. **The amount of flux to be carried by the core will depend on the size or wattage rating of the transformer.**

The primary winding is to excite or magnetize the core and provide a magnetic flux to induce the desired voltage in the secondary winding. The number of turns and size of wire in the primary winding will depend on the applied voltage and the desired power rating.

You have already learned that the secondary voltage of any transformer will depend on the voltage applied to the primary and the ratio of primary to secondary turns.

Therefore, the principal factors to be determined in building a transformer are the core size, area and weight; the number of turns and size of wire for primary and secondary windings, the number of turns per volt in the windings, and the amount and grade of insulation.

Important points to keep in mind in the construction of any transformer are:

Do not skimp on core iron, wire size or insulation. Liberal core size means higher efficiency and requires less turns of wire per volt. Ample wire size prevents overheating. Careful and sufficient insulation tends to prevent breakdowns due to short circuits or voltage flash overs.

Before trying to determine the size or area of the core we should decide which type of core we desire to use. The two best types for simple transformer construction are the "core type," and the "shell type" shown in Figures 99 and 100 of this Section.

The plain "core type" with four legs or sides, is often the easiest to build, and when voltages of 1000 or over are desired on the secondary, it is much easier to insulate the winding on this type of core. The shell type core is somewhat more efficient and compact and not very difficult to build.

As a general rule, we should allow a core area of at least 6 square inches for a transformer of 1 kilowatt size. It is also customary to allow a flux density of 50,000 lines per square inch of core if the core iron is of a good grade of silicon steel. For continuous duty without overheating, we should allow 1000 to 1200 circular mils of wire area per ampere of load, on both primary and secondary windings. For intermittent or temporary duty, on very small transformers that are easy to cool, and where efficiency is not so important, this allowance may run somewhat lower, from 600 to 800 C.M. per ampere.

The number of turns required in each coil will be proportional to the applied or induced voltage, and inversely proportional to the cross sectional area of the core. A convenient figure for rough design or checking of small transformers is 7 turns per volt, for a core area of 1 square inch, if the transformer is to be used continuously; or 4 turns per volt if it is to be operated for only a few minutes at a time.

The relations between volts, amperes and watts in tranformer design can easily be determined by the use of ohms and watts law formulas with which you are already familiar.

For simplicity and convenience in securing practical design data for small transformers, we have prepared the following table, which gives all the necessary values on core area, wire size and number of turns for six sizes of transformers ranging from 50 watts to 1500 watts.

This data is given for transformers that are intended for use on 110 volt circuits. That is, their primary windings are designed for 110 volts at 60 cycles frequency.

Watts Input	Core Area	Turns Per Volt	Number of Pri. Turns	Size of Pri. Wire
50	1¼ x 1¼	4.8	530	23
100	1½ x 1½	3.3	365	20
250	1⅞ x 1⅞	2.25	250	16
500	2⅛ x 2⅛	1.66	185	13
1000	2½ x 2½	1.2	130	10
1500	2¾ x 2¾	1.	110	9

The above sizes of transformers would be convenient for bell circuits, signal circuits, electrical toys, neon signs, testing insulation, small spot welders, tesla coil operation, etc. The three larger ones might be used for light and power purposes. The number of turns and size of wire for the secondary windings is not given, as this will depend on the desired secondary voltage or whether the transformer is to be a step-up or step-down unit.

The number of secondary turns can be easily determined for any desired voltage by multiplying the turns per volt given in the table, by the desired voltage. The full load secondary current can be determined by dividing the wattage rating of the tranformer by the secondary voltage. Then the C. M. area of secondary wire can be determined by multiplying the current by 1000, and getting the gauge number to correspond from a wire table.

Another convenient method of getting the various design figures for small transformers of any size from 50 watts to 1000 watts is by use of the chart or graphs shown in Fig. 153-A.

For example, suppose we wish to determine the values for a 500 watt, or 500 volt-ampere transformer.

The weight of the core is found by running horizontally along the 500 V.A. line to the solid line A, and then vertically down to the top row of figures marked weight of core. We find the core weight to be 25 pounds.

The core width can be found by running horizontally along the 500 V.A. line to the curve Y, and then down to the middle line of figures, marked width of core, where we read slightly over 2 inches. Call it 2 inches.

In this particular design the core depth is assumed to be 1½ times core width, or in this case, 3 inches. Then the core area will be $2 \times 3 = 6$ inches. This is somewhat more liberal core design than given in the foregoing table, but will make the required turns per volt a little lower, and the transformer efficiency a little higher. It will also change some of the other values slightly, but they are all close enough for practical purposes, whether taken from the table or the chart.

To find the turns per volt, locate the core area or 6, on the bottom line of figures and run vertically up to curve T, and then horizontally over to the left column of figures, and we find 1.4 turns per volt.

Then multiply this figure by the primary voltage to determine the number of primary turns, and by the desired secondary voltage to determine the secondary turns. If the primary voltage is 110 volts, then 1.4×110 equal 154 turns. If the desired secondary voltage is 10, then $1.4 \times 10 = 10 = 14$ turns for the secondary.

The primary current at 500 V.A. will be $500 \div 110$ or 4.5 amperes. Assuming that this transformer is only intended for intermittent duty, and allowing 600 C.M. per ampere, we find that $600 \times 4.5 = 2700$ C.M. wire area required. From a wire table we find that a #15 wire is suitable.

The secondary full load current would be $500 \div 10 = 50$ amperes. Then $50 \times 600 = 30{,}000$ C.M. this would require a #5 wire, or two #8 wires in parallel for better flexibility than the heavy wire.

Values for transformers of other sizes such as 50, 100, 250, 750, or 1000 volt-amperes, and any primary or secondary voltages can easily be determined from this same chart and the simple rules and calculations in the foregoing example.

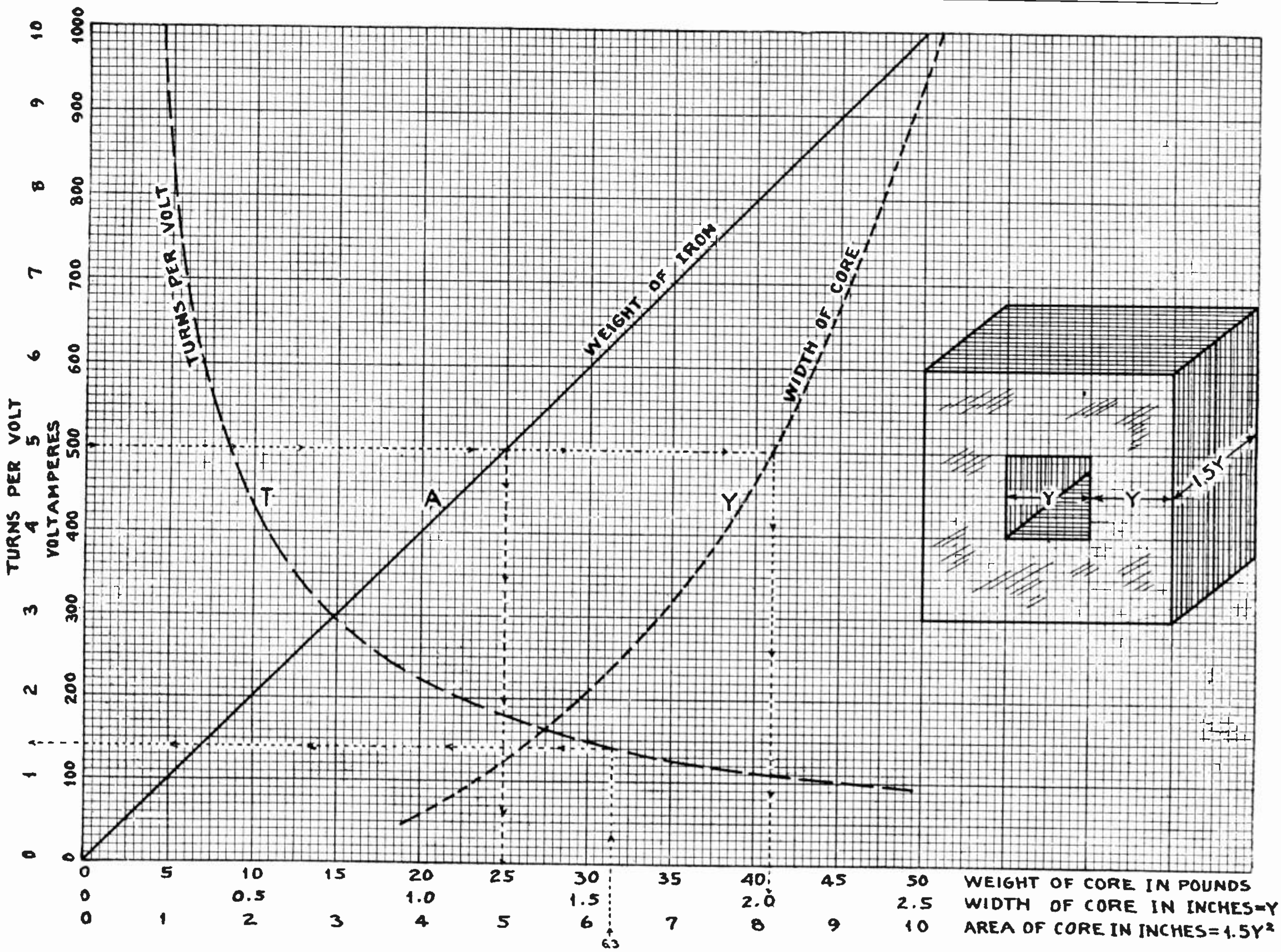

Fig. 153-A. Transformer design chart.

163-A. TRANSFORMER FORMULAS

The following data and formulas may at times be very convenient for designing transformers of other sizes than those for which the data has been given in the accompanying table and chart.

As previously mentioned, the size of a transformer core as well as the size of wire in the primary, depends on the wattage or volt-ampere rating. The primary wattage also has a bearing on the "volts per turn" of wire in the primary.

It is often desirable to have two or more separate secondary windings on a transformer, for obtaining different voltages and different amounts of current. In this case, the primary wattage can be determined by adding up the wattages of all secondaries and then adding about 10% more for losses in the transformer.

After the primary wattage has been determined, the volts per turn can be found by the formula:

$E = \frac{Wp}{50.}$ for 60 cycle transformer of the plain "core type," or

$E = \frac{Wp}{83}$ for 25 cycle transformers of the plain "core type," or

$E = \frac{Wp}{25}$ for 60 cycle transformers of the shell "core type," or

$E = \frac{Wp}{41}$ for 25 cycle transformers of the shell "core type."

In these formulas:

E=volts per turn
Wp=primary watts

The figures 50, 83, 25 and 41 are constants which have been worked out for your convenience, and to simplify the formulas.

As the "turns per volt" is often only a fraction, it is convenient to change this factor to "volts per turn" by simply inverting the fraction.

For example, if the volts per turn should be 1/6, then the turns per volt would be 6.

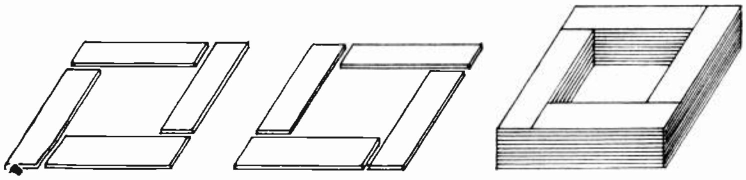

Fig. 153-B. A core type transformer core may be constructed with alternate layers of laminations as shown above.

After finding the turns per volt, the required number of turns for either the primary or secondary winding can be found by simply multiplying the turns per volt by the voltage to be applied to the primary, or the induced voltage desired in the secondary.

In other words:—N = V × Tv.

In which N=number of turns

V=voltage across the coil

Tv=turns per volt.

The full load current of either winding can be determined by dividing its wattage rating by its voltage. Then the size of wire for either winding can be determined by multiplying the current in amperes by 600 to 800 C.M. for small well ventilated transformers, or those for intermittent duty; or by 1000 to 1200 C.M. for larger transformers with deeper windings, and for continuous duty.

The area of the core can be determined from the formula:—

$$A=\frac{E \times 100{,}000{,}000}{4.44 \times F \times B}$$

In which

A=area of core in sq. in.

E=volts per turn

100,000,000=number of lines of force to cut in one sec. to produce one volt.

44.4=a predetermined constant

F=frequency of primary supply

B=number of lines for force per sq. inch.

Allowing 50,000 lines of flux per square inch of core as previously mentioned, if we work out this formula for a 60 cycle transformer it becomes:

$$A=\frac{E \times 100{,}000{,}000}{13{,}320{,}000}, \text{ or } A=E\times 7.5$$

For 25 cycle frequency the formula becomes:

$$A=\frac{E \times 100{,}000{,}000}{5{,}550{,}000}, \text{ or } A=E\times 18$$

These formulas have been first given in full, and then reduced down, in order to show you the factors involved and to simplify the final formula for your use in designing transformers. With a little practice you should find it quite easy to determine core and winding data for various transformers by the use of the foregoing formulas.

163-B. GENERAL INFORMATION ON TRANSFORMER CONSTRUCTION

When we refer to core area, we mean the area of one leg only, or the area of the magnetic path at any point in its circuit.

The required area can be obtained by stacking laminations to form a square core, or a core 1½ to 2 times as deep as it is wide, or other rectangular shapes.

The length of the core sides should be kept as short as possible and still allow the proper sized window or center opening to accomodate the windings. The shorter the core or magnetic path, the better will be the regulation of the transformer, but one must be careful not to get the window too small.

The required window size can be determined by taking the wire diameter (including insulation) from a wire table, and then calculating the number of turns per sq. inch, and allow a little extra space for insulation of the coil layers. On many small transformers the window size need not be any larger than the area of the core leg, but on other transformers for high voltages, the window may need to be two or three times the core area.

Transformers will be more efficient if only thin good grade laminations are used. No. 26 or No. 28 gauge are generally best for small units.

When assembling the core laminations, be sure to carefully lap the joints as shown at C in Fig. 153-B, so that the magnetic leakage and reluctance will be kept as low as possible.

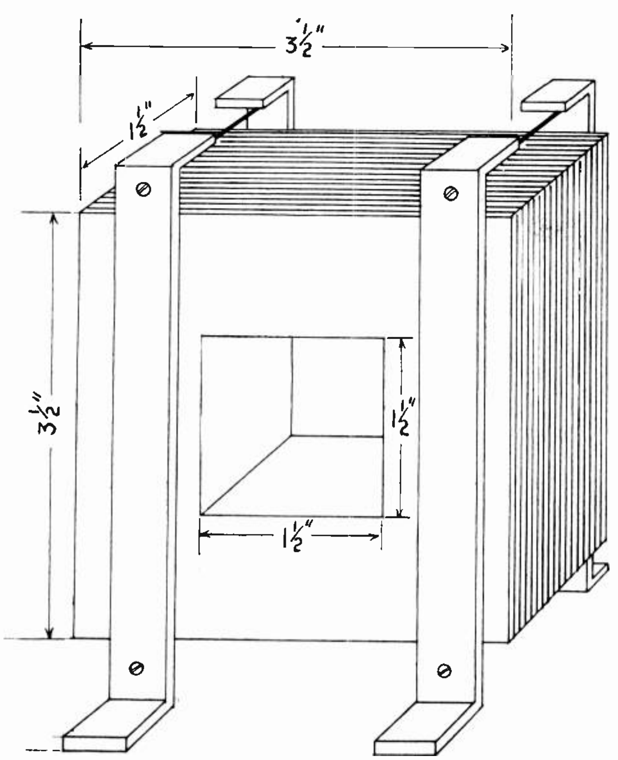

Fig. 153-C. A 50 w. transformer core constructed from strips 1"x2½". Note the method of binding the strips together.

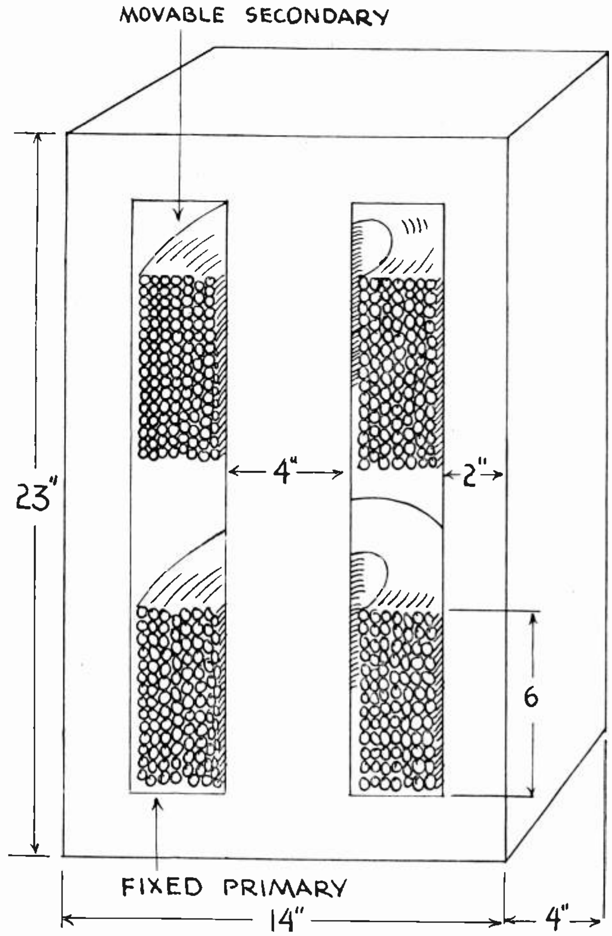

Fig. 153-D. A 10 Kv-a. welding transformer designed for operation on a 220 volt line.

If old laminations are used, they should be cleaned, but be careful not to scrape the oxide film or insulation from them, as each lamination should be insulated from adjacent ones to keep down eddy currents. For this same reason, care should be taken not to leave rough or burred edges on the laminations.

When preparing to clamp the laminations, it is best to use clamps and external bolts as shown in Fig. 153-C, rather than to drill holes through the laminations and possibly short them together.

When using old core laminations, if their coating of oxide or varnish has been destroyed they can be coated with a thin insulating varnish.

For the best efficiency, the copper and core losses should be about equal.

In arranging the windings on the core, the primary and secondary coils may be placed on opposite legs of the core, or they can be placed one over the other on the same core leg. The closer they are together, the better will be the regulation of the transformer.

If several different voltages are to be obtained from the secondary, several separate windings can be used, or the secondary winding can be tapped at proper points and individual leads brought out for the different voltages.

If the current load is to be different on the various sections of the secondary, then they are commonly wound separately and should use different sizes of wire according to their load in amperes. For example, we might have one secondary winding of 5000 turns of No. 30 wire, and another of 3 turns of 0000 cable on the same transformer.

When windings are placed one over the other on the same core leg, the lower voltage winding is often placed next to the core because of less difficulty in insulating it from the core. This is not always the case, however.

Windings should be carefully insulated from the core, preferably with a fibre spool, or at least with a wrapping of several layers of heavy oiled paper or tape. Fibre end collars help to hold the wires in place in the coil layers, and also insulate them from the core.

Each layer of wire should be wound neatly and evenly, avoiding crossed wires as they tend to cut through their insulation and short circuit if pressed too tightly together.

Each layer should be insulated from the others by a layer of oiled paper or varnished cloth. **Great care should be used to prevent end turns of one layer dropping down near the turns of layers deeper in the winding** as this will generally result in a short circuit and cause the entire winding to fail and necessitate rewinding. This is particularly true on high voltage windings. End turns can be held securely in place by placing short pieces of thin tape under the last several turns and then folding the free ends of the tape back over these turns and binding them down with the next layer.

Starting and finish leads of each coil should be protected and anchored by covering with spaghetti tubing several turns into the coil to prevent their being broken off. On windings using very small wires, short pieces of heavier wire are often soldered on at the ends and used for the several end turns, being well bound into the coil to relieve the small wires of any strain.

Don't skimp on insulation, or it will frequently result in breakdowns or shorts, and necessitate complete rewinding. On the other hand, don't pile up unnecessarily thick layers of insulation, as these tend to prevent the escape of heat to the outside of the winding and may cause hot spots. Mica is very good insulation for the core, and for high voltage windings.

Magnet wire for transformer winding is generally insulated with one or two layers of cotton, and sometimes a layer of thin enamel of high dielectric strength to prevent voltage breakdown or puncture.

The cotton affords good mechanical protection to the enamel as well as some added insulation value.

Where the wires are fairly large, or with smaller wires that are machine wound, plain enameled wire is sometimes used. This makes possible a very compact winding, and permits very free flow of heat to the outside of the winding. Cotton is much more of a heat insulator than is enamel.

After a winding is completed, it should be covered with one or two layers of tape, cloth or paper and shellaced or varnished for mechanical protection to the wires, for neater appearance and to keep moisture and dirt out of the windings.

When convenient, it is often well to dip finished transformer coils in hot insulating wax or compound, to exclude moisture and to bind the turns more securely in place.

When winding coils, a wooden form just slightly larger than the core leg makes a convenient coil form. Slightly tapering this form, and wrapping with a layer or two of waxed paper makes it easier to remove the finished coil. Winding a layer of cord on the form first, and then pulling out this cord also simplifies removing the finished coil.

When repairing or rewinding damaged transformers, **always observe and carefully record the size of wire, number of turns, and the grade and amount of insulation removed so you can duplicate them in the new winding.**

Careful workmanship and liberal or safe design allowances, on size of core and wire, and on insulation should enable you to do many profitable and satisfactory transformer construction or repair jobs. Building one or more small transformer is well worth the cost of time and materials just for the experience and confidence it will give you.

163-C. WELDING TRANSFORMERS

A practical arc welding transformer can be built with a core such as shown in Fig. 153-D, using about 220 lbs. of iron, and 86 turns of No. 3 wire on the primary, and 45 turns on No. 1 wire on the secondary.

This unit is for operation on 220 volts, and is capable of supplying secondary currents up to 200 amperes.

Square wire should be used in these windings if possible to avoid waste space between turns. The layers of the winding should be spaced with ⅛″ wood strips to permit ventilation. The secondary coil should be arranged so it can be moved up or down on the core leg to permit varying the welding current for different jobs.

Such a transformer can also be used for thawing out frozen pipes, by connecting its secondary leads to a length of frozen pipe, and adjusting the current to warm the pipe, but not to overheat it.

163-D. BELL RINGING OR TEST TRANSFORMER

A practical 50W transformer may be constructed with core dimensions shown in Fig. 153-C, but for experience, let us work out the design from the information just covered.

Our first step is to determine the size of window opening necessary for the primary and secondary coils. So by referring to the table on page 39, we find that a 50W transformer primary should have 530 turns of No. 23 wire. The number of secondary turns will be found by multiplying the desired voltage by 4.8 (the number of turns per volt shown in the table.) Assuming that we desire a 12 volt secondary, we multiply 12 by 4.8 and obtain 57.6, (use 58) as the number of turns necessary.

The secondary current is found according to Watts law by dividing Watts which in this case is 50 by the volts. So the secondary current will be 50 ÷ 12 or 4 + amperes.

We have learned that for intermittent use 600 C.M. per ampere is required. Therefore, 600 C.M. × 4 amperes = 2400 C.M. Referring to a wire chart, we find that No. 16 wire has a circular mill area of 2583 which should be ample.

The winding space may be determined by referring to Fig. 13, Armature Winding Section 1. The chart shows that 1″ will take 1293 turns of #23 wire so ½″ will be ample for 530 turns. Number 16 requires 1″ for 282 turns, so 58 turns will require about .3 of one inch. Adding .5″ and .3″, we obtain .8″ or less than one inch actual winding space, but since we must allow for insulation, a window of 1″ square would be rather crowded. In order to insure having plenty of room, let us use a window opening 1½″ × 1½″.

The length of the laminations will be equal to the length of the window, plus the width of the laminations. In this case, the window length of 1½″ × 1″, (the width of the laminations) gives us a lamination length of 2½″.

The chart in Fig. 153-A shows that about 2½ lbs. of iron will be required. The amount of wire may be estimated by multiplying the number of turns by the average length per turn, and then referring to wire charts which show the number of ft. per pound. In this case, ½ lb. of #23 will be ample for the primary, and about 4 oz. of #16 will be required for the secondary.

The core may be stacked with alternate layers as shown by Fig. 153-B, A and B. The first layer may be arranged as at A and the second layer as at B, the third as at A, etc. This arrangement breaks joints so that the completed core may be bound rigidly together as shown at C.

After the core is assembled, three sides should be temporarily bound together with tape, and the remaining side should be removed so that the coils may be placed on the core.

After the core legs are insulated, and the coils placed on the core, the strips may be replaced and the completed core may then be permanently bolted together with strips of wood, or pieces of strap iron or angle iron. A piece of insulating material such as fibre or wood should be attached to the core to make a mounting base for the terminals. The secondary coil may be tapped at the 29th turn to provide 6 volts.

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ALTERNATING CURRENT POWER
AND
A. C. POWER MACHINES

Section Five

Alternating Current Motors
Types, Construction, Principles, Characteristics
Single Phase and Polyphase Motors
Squirrel-Cage Induction Motors, Slip Ring Motors,
Synchronous Motors
Special Motors
Power Factor Correction
Proper Selection and Loading of A. C. Motors
Static Condensers, Synchronous Condensers
Power Factor Correction Problems
Calculation of Condenser Sizes

ALTERNATING CURRENT MOTORS

By far the greatest part of all the electrical energy generated is used for power purposes, and most of this mechanical power is developed by alternating current motors.

A. C. motors are made in sizes from 1/1000 h. p. and less, up to 60,000 h. p. and over, and they can be built even larger if any need for more powerful motors arises.

A. C. motors are made to meet almost every conceivable need and condition in the driving of machinery and equipment of all kinds. Some of the latest type A. C. motors are designed to produce excellent starting torque and give a wide range of speed control, and many other desirable characteristics which it was formerly thought possible to obtain only with D. C. motors.

Alternating current motors have the advantage of practically constant speed; and the A. C. squirrel-cage induction motor, which is the most commonly used type, **has no commutator or brushes and therefore eliminates all sparking and fire hazard and reduces the number of wearing parts.**

A. C. motors are quiet, safe, and efficient in operation, and very convenient to control, and are therefore an ideal type of power device. An operator can start or stop a unit of several thousand h. p. by merely pressing a button of an automatic remote controller such as is used with many large A. C. motors.

A. C. electric motors are rapidly replacing steam and gas engines and other forms of power in older factories; and practically all new factories, mills, and industrial plants are completely operated by electric motors. Millions of A. C. motors are in use in machine shops, wood working shops, saw mills, automobile factories, and industrial plants of all kinds.

Fig. 154 shows a group of A. C. motors driving machines in a textile mill, and Fig. 155 shows two large motor-driven planers in a wood working plant.

Motor installation and maintenance provides one of the greatest fields of opportunity in the entire electrical industry, for trained men to cash in on their knowledge in interesting and good paying work.

164. TYPES OF A. C. MOTORS

Alternating current motors are made in a number of styles or types, depending upon the class of service and type of power supply they are intended for. The most common of these are the **repulsion, induction**, and **synchronous** types.

Repulsion motors are used on single-phase circuits only, but induction and synchronous motors are made in single-phase, two-phase, and three-phase types.

Single-phase motors are most commonly made in sizes from ½ to 10 h. p., although in a few cases larger ones are used. They are usually wound for circuits of 110, 220 or 440 volts.

Two-phase motors are still in use to some extent in a few older plants and factories, but the great majority of A. C. motors are three-phase. Three-phase motors are commonly made in sizes from ½ h. p. to several thousand h. p. each, and can be made as large as any present requirements demand.

Fig. 156 shows a 3000-h. p., A. C. induction motor in use in a modern steel mill. The control panel is shown at the left of the motor.

165. VOLTAGE RATINGS AND SPEEDS

The majority of three-phase motors are operated at 220, 440 and 550 volts, but many of the larger ones of several hundred h. p. and up, are designed for voltages of 1100, 2300, and up to 12,000 volts.

Medium-sized A. C. motors are commonly made to operate at speeds ranging from 900 to 3600 R.P.M. and very large motors operate at lower speeds, from 200 to 600 R.P.M. Very small single-phase motors of the repulsion or series universal type are made to operate at speeds from 4000 to 12,000 R.P.M.

Power motors of the higher speed types develop more h. p. for a given size than the low speed motors.

166. CONSTRUCTION FEATURES AND GENERAL PRINCIPLES

A. C. motors are also made with various types of open and enclosed frames, to adapt them to uses in different locations and under various conditions.

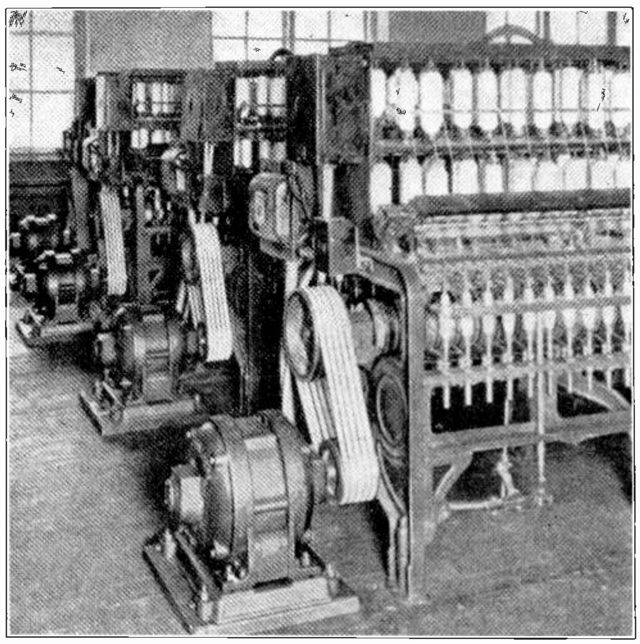

Fig. 154. This photo shows a group of machines in a textile mill, each of which is driven by an individual A. C. motor.

Fig. 157 shows a 5-h. p., three-phase, 220-volt, induction motor of a common type, such as is used by the tens of thousands in this country for turning the wheels of industry.

Fig. 158 shows an A. C. motor with an enclosed-type frame, which keeps all dust and dirt from its windings.

The constructional features and general operating principles of A. C. motors have been covered in this Reference Set in Section Two of Armature Winding, and so they need not be repeated in detail here. It will be a very good plan for you to carefully review Articles 66 to 75 inclusive and to re-examine Figs. 45 to 57 in Section Two of Armature Winding, and get these points well in mind again before proceeding further with this section.

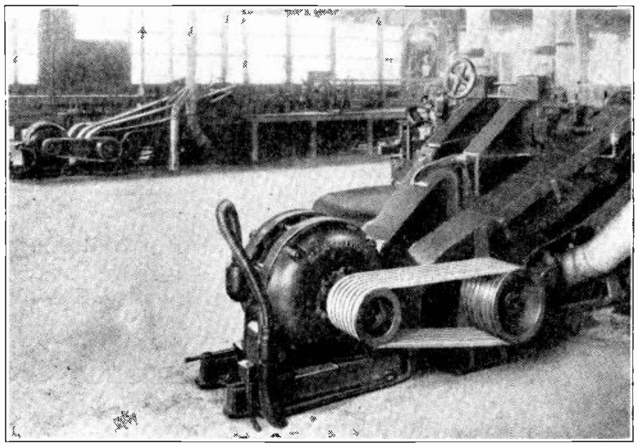

Fig. 155. An A. C. induction motor in use for driving a woodworking machine. The motor is connected to the machine by means of a special rope drive. (Photo courtesy Allis-Chalmers Mfg. Co.)

You have already learned that the principal parts of ordinary A. C. induction motors are the stator and rotor.

You will recall that the stator is commonly connected to the line and receives alternating current which sets up a revolving magnetic field around the inside of the stator winding. This revolving flux cuts across the bars or windings of the rotor, inducing a secondary current in them, and the reaction between the flux of the rotor currents and that of the revolving stator field produces the turning force or motor torque.

Fig. 159 shows the stator of an A. C. induction motor, and Fig. 160 shows a squirrel-cage rotor for the same type motor. Fig. 161 shows a sectional view of an induction motor, with the rotor in place inside the stator core.

Some A. C. induction motors have wire windings on their rotors, instead of bars such as are used on squirrel-cage rotors. These wire-wound rotors are called **phase-wound** rotors and will be explained in later paragraphs.

167. MOTOR CHARACTERISTICS

Each of the different types of A. C. motors has certain different characteristics with respect to their starting torque, load "pull out" torque, speed regulation, power factor, efficiency, etc. It is very important for you to know these different characteristics and to be able to compare them for various motors, so you will be able to select the proper motors for the various power drives and applications you may encounter on the job.

Some of these motor characteristics you are already familiar with from your study of D. C. motors; while others apply only to A. C. motors and are covered for the first time in this section.

Motor characteristics depend largely on their design, and therefore the characteristics of any certain type of motor can be varied considerably by the manufacturers. Motors are available in common types with the required characteristics for most any power need, and for special requirements the designers and manufacturers can build motors of just the proper type to fit the needs of most any job.

In the following pages we shall take up each common type of A. C. motor separately, and thoroughly explain its principles, characteristics, and applications.

Before doing this, however, there are a few general terms and expressions which apply to all A. C. motors and with which you should be familiar. These terms will be frequently used in explaining the various motors, and if you will carefully familiarize yourself with them now, it will make the following material much easier to understand.

168. SYNCHRONOUS SPEED

The term **synchronous speed** as used in connection with A. C. motors refers to the speed in R.P.M. of the rotating magnetic field which is set up around the stator by the current supplied from the line.

Synchronous motors revolve at the same speed as the rotating magnetic field in their stators, and thus maintain constant speed as long as the **frequency** of the line current remains unchanged.

The speed of the rotating magnetic field of any A. C. motor and the operating speed of synchronous motors depend upon the frequency of the current on which they operate and the number of poles in their stator winding.

This synchronous speed can always be found by the simple formula:

$$S = \frac{120 \times f}{p}$$

In which:

S = synchronous speed in R.P.M.
f = frequency in cycles per sec.
p = number of poles in the motor.
120 = twice the number of seconds in one minute.

The constant 120 is used instead of 60 seconds per minute, because a pole of the rotor must pass one pair of poles during each cycle.

For example, if a four-pole motor is operated on

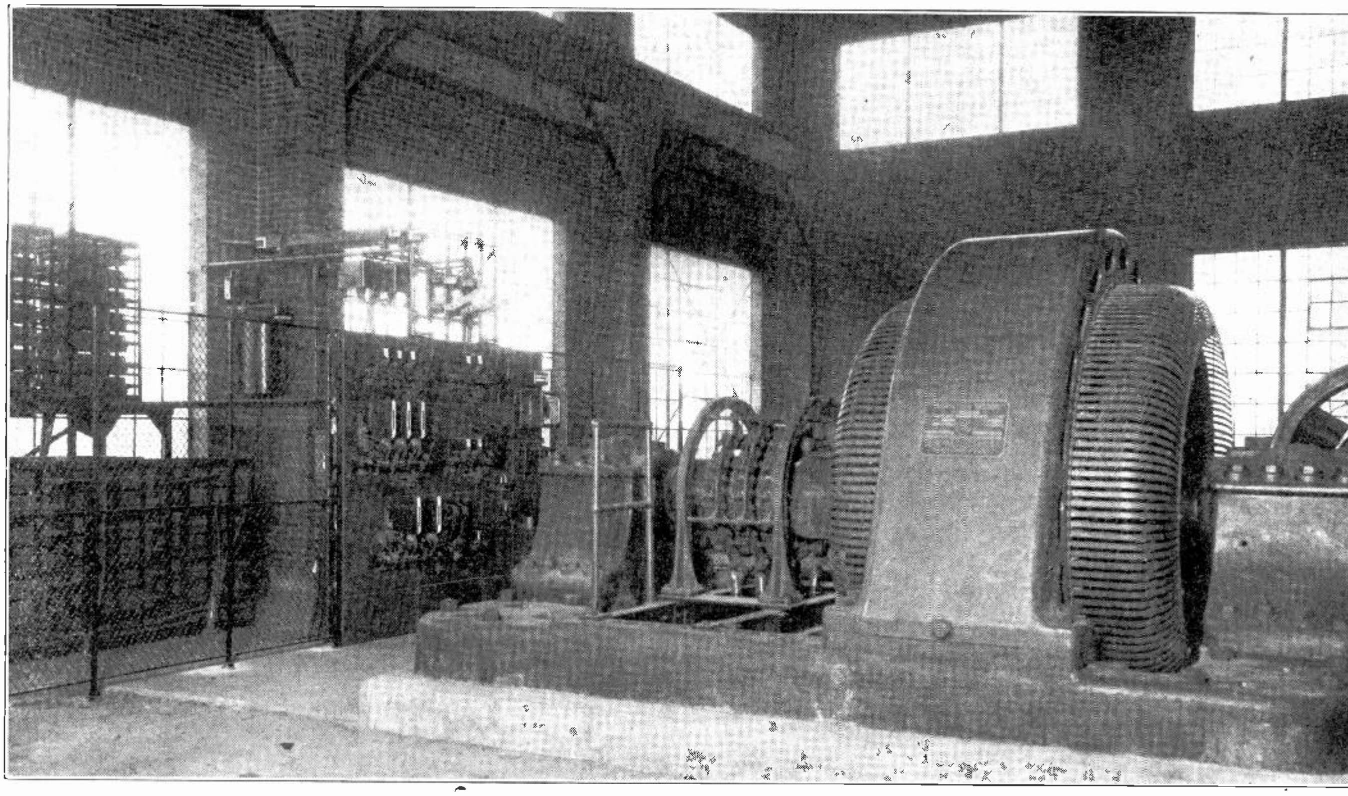

Fig. 156. This photo shows a 3000-h. p., 375 RPM, A. C. induction motor in use in a steel mill. Note the control panel and resistors for starting and speed regulation shown in the left of this view. (Photo Courtesy General Electric Co.)

a 60-cycle circuit, its synchronous speed will be:

$$S = \frac{120 \times 60}{4}, \text{ or } 1800 \text{ R.P.M.}$$

169. SLIP

A. C. induction motors never operate at exactly synchronous speed, as their rotors must always turn at slightly lower speed than the rotating magnetic field, in order that the lines of force will cut across the rotor conductors and induce the necessary current in them.

This difference between the actual operating speed of induction motors and the speed of their rotating magnetic fields is called the **slip** of the motor. The slip is generally expressed in per cent. of synchronous speed.

For example, if a six-pole induction motor is operated on a 60-cycle circuit, it will have a synchronous speed of 1200 R.P.M., but its actual speed when fully loaded is only 1140 R.P.M.

To find the per cent. slip, we can divide the amount of slip by the synchronous speed, or in the case of the motor just mentioned, 1200 — 1140 = 60 R.P.M. of slip, and $\frac{60}{1200} = .05$, or 5%, slip.

The slip of a motor will vary with the amount of load. Increasing the load causes the rotor to slow down a little and allows the magnetic field to cut across the rotor conductors more rapidly, and thereby develop in the rotor the increased amount of induced current needed to maintain the added torque for the heavier load.

The slip of various induction motors usually ranges from 2 to 8 per cent., according to the size and type of motor and the amount of load connected to it. The larger motors have less slip than small ones do.

170. TORQUE: STARTING, FULL LOAD and PULL-OUT

You have already learned that the term **torque** applies to the twisting or turning effort developed by a motor. Torque is expressed and measured in

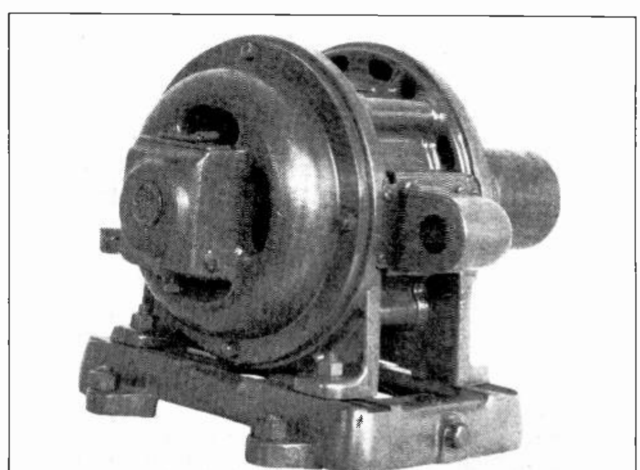

Fig. 157. Common type of 5-h. p. A. C. induction motor. Motors of this type are used by the thousands in factories and industrial plants throughout the country. (Photo courtesy General Elec. Co.

pounds-feet; a torque of twenty pounds-feet being equal to a pull of 20 lbs. at a radius of one foot, or a pull of 10 lbs., at a radius of 2 feet, etc.

You have also learned that the important torque values to consider in selecting motors of proper characteristics, are: the **starting torque, full load torque,** and **pull-out** or **stalling torque.**

The full load torque of a motor is taken as a base and the starting and stalling torque are compared with it, and expressed as a certain percentage of the full load torque. For example, if a motor has a full load torque of 15 pounds-feet, and a starting torque of 30 pounds-feet, the starting torque is two times the full load torque, or 200%.

As the full load torque is used as a base for comparison, it is important to have some means of determining this torque. The full load torque of a motor can be found by the following formula.

$$T = \frac{5252 \times H.P.}{R.P.M.}$$

In which:

T = full load torque in pounds-feet.
5252 = constant.
H.P. = horse power rating of motor.
R.P.M. = motor speed in rev. per min.

As an illustration, if a 10 h. p. motor has a speed of 1800 R.P.M., its full load torque would be:

$$\frac{5252 \times 10}{1800}, \text{ or } 29.2 \text{ — pounds-feet}$$

The **starting torque** or turning effort exerted by a motor during starting is very important and should always be considered when selecting motors

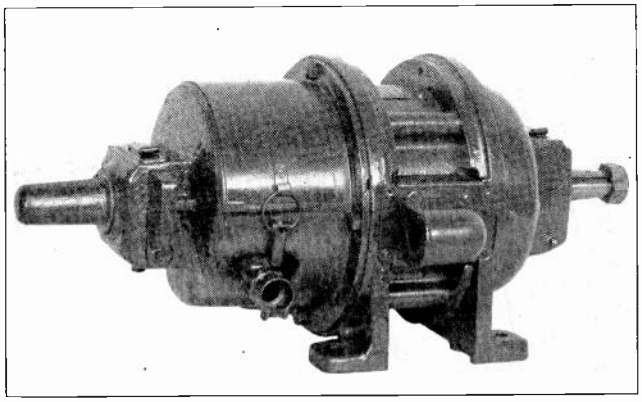

Fig. 158. A. C. induction motor with totally enclosed frame to keep out dust and dirt from the windings and also prevent fire and explosion hazard. (Photo courtesy General Electric Co.)

that are to start up under heavy loads. The starting torque of common induction motors will vary from 2 to 5 times the full load torque, according to the design of the motor and the amount of line voltage applied during starting.

The starting torque of an induction motor varies directly with the square of the applied voltage during starting.

The **pull-out** torque of a motor is the torque required to cause the motor to pull out of step with

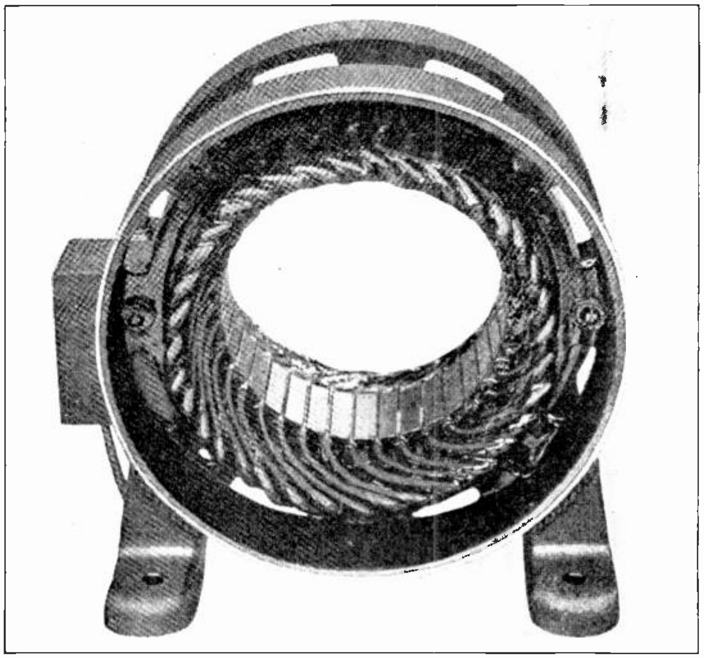

Fig. 159. This view shows a stator of an induction motor with the end shields and rotor removed. When A. C. is applied to the winding a revolving magnetic field is set up around the inside of the stator core.

the line frequency, slow down, and come to a complete stop if the overload which exceeds the pull-out torque is left on the machine. In other words, **the** pull-out torque expresses the ability of a motor **to** carry overloads without stalling.

The pull-out torque of common A. C. motors ranges from 1½ to 3 times full load torque.

The starting torque, full load torque, and pull-out torque of an A. C. motor can be found by means of the brake horse-power test which was explained in Articles 142 and 143 in Section Three of Direct Current Motors.

171. EFFICIENCY AND POWER FACTOR

As you have already learned, the efficiency of any motor is the ratio of its output to input, or

$$\text{eff.} = \frac{\text{Mech. h. p. output}}{\text{Elec. h. p. input}}$$

The mechanical h. p. output of any motor can be determined by means of the brake h. p. test, and the electrical h. p. input can be found by using a wattmeter or voltmeter, ammeter, and power factor indicator, and then dividing the watts by 746.

The efficiency of A. C. motors varies with their design and also with their size. The efficiency of common induction motors generally ranges from about 78% to 82% on motors of 1 to 5 h. p., and up to 90% or better on motors from 25 h. p. to several hundred h. p.

The efficiency of any A. C. motor is always higher when the motor is operated at or near full load, and becomes much lower when the motor is operated lightly loaded.

This is also true of the power factor of A. C.

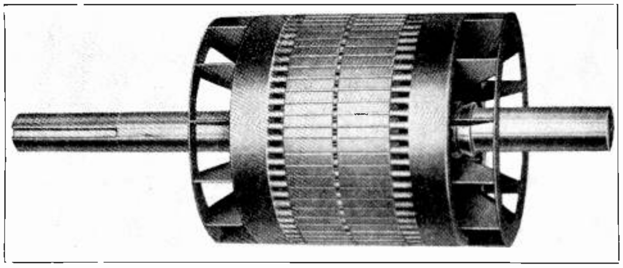

Fig. 160. Squirrel-cage rotor from an A. C. induction motor. Note the manner in which the bars are imbedded in the core slots and also note the ventilating fans at the ends of the rotor.

motors. The power factor of large motors is usually higher, ranging from 78% to 85% for motors of 1 to 5 h. p. to 93% for motors of 200 h. p. and up. **The power factor of an induction motor is much better when the motor is fully loaded, and is very poor when motors are operated lightly loaded or without any load.**

The method of determining the power factor of any A. C. machine or device was explained in Articles 36 to 41 of Section One on Alternating Current.

Very often in ordinary field problems, where approximate figures are all that are required, if the power factor and efficiency of certain motors are not known, they are both assumed to be about 80% for induction motors of 1 h. p. to 10 h. p., and about 88% for motors of 10 to 50 h. p.

Synchronous A. C. motors can be made to operate at 100% or unity power factor, or even at a leading power factor if desired, by properly exciting their D. C. fields. This will be explained in the section on synchronous motors.

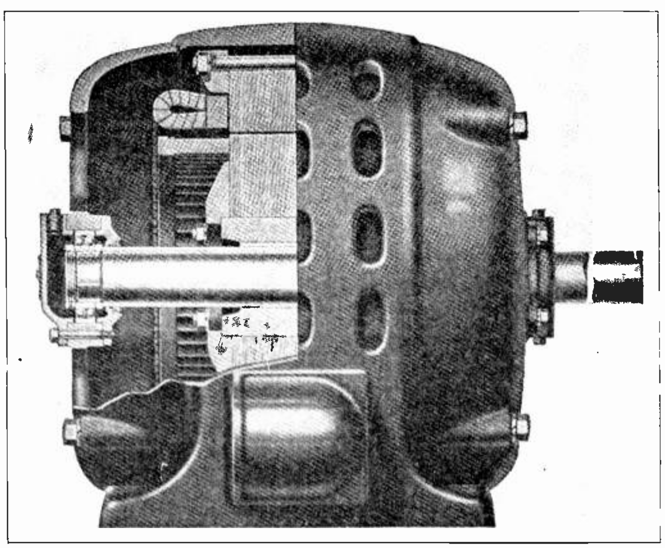

Fig. 161. Sectional view of a squirrel-cage induction motor showing the position of the rotor and bars with respect to the stator core and winding.

172. HORSEPOWER, VOLTAGE and FREQUENCY RATINGS

Motors as well as other electrical machinery have their load ratings or maximum output capacity determined by the heat developed in them. A. C. motors heat up due to copper losses and core losses, as explained in the section on transformers. The horse power rating of any A. C. motor is the load it can carry continuously without overheating.

Unless otherwise specified, motors are usually rated at full load with a 40° C. rise in temperature. Most A. C. motors are designed to carry overloads of not over 25% for periods of 2 hrs. with a temperature rise not exceeding 55° C.

Nearly all modern motors have their h. p. ratings and temperature rise limits stated on their nameplates.

The voltage given on the name-plate of a motor is the proper voltage at which the motor should be operated. Practically all ordinary A. C. motors are designed to give full-load rating as long as the voltage does not vary more than 10% above or below normal, provided other conditions are normal.

A. C. motors will develop full rated h. p. on frequencies not exceeding 5% variation above or below the normal frequency for which they are designed, provided the voltage and other conditions are normal.

If the voltage and frequency of the line are both off normal, their combined variation should not exceed 10%.

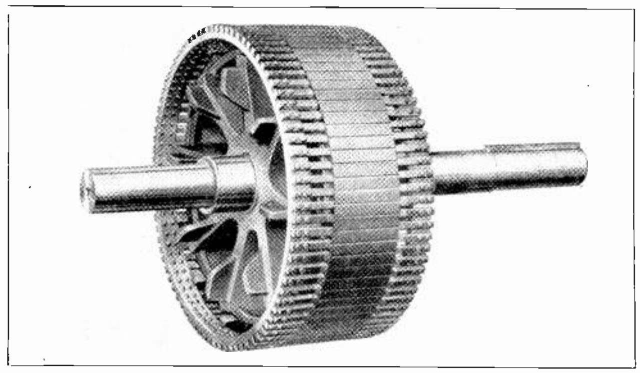

Fig. 161-A. This photo shows an excellent view of a squirrel-cage rotor using square bars which are riveted to heavy end rings.

173. CURRENT RATINGS

The name-plate current rating of an A. C. motor refers to the current required by the motor at full load. This current can also be found by placing an ammeter in any one of the line leads to the motor when it is operating at full load.

For example, a three-phase motor having a nameplate rating of 25 amperes should give an ammeter reading of 25 amperes in each of the three line leads to the motor, when operating at full load.

The approximate current of a three-phase motor can easily be determined by the following formula:

$$I = \frac{\text{h. p.} \times 431}{\text{eff.} \times \text{P. F.} \times E}$$

This is a simplified formula used to shorten the working of such problems. The current can also be found by first converting the h. p. into watts and dividing this by the product of efficiency and power factor to get the apparent power; and then using the three-phase current formula given in Article 45 of Section One on A. C.

The table in Fig. 162 gives the approximate currents for standard A. C. squirrel-cage induction motors of different h. p. and voltage ratings, and of single, two, and three-phase types.

Special squirrel-cage motors with high reactance rotors, and motors with phase-wound rotors may take from 1 to 5 amperes more than the current ratings given in the table for the same h. p. and voltage.

174. SINGLE-PHASE MOTORS

Single-phase motors are quite extensively used in small sizes, ranging from ¼ h. p. or less to 10 h. p. for general purposes. Special single-phase motors for railway service are sometimes made as large as several hundred h. p., but for general industrial power purposes they are seldom made larger than 10 h. p.

Small single-phase motors from ⅙ to ½ h. p. find a very wide application in the operation of small power-driven machines in homes and small shops, where it is desirable to operate these devices from the ordinary single-phase lighting circuits.

Washing machines, electric ironers, oil burners, refrigerators, fans, pumps, drill presses, etc., are commonly driven by motors of this type.

Some idea of the great extent to which fractional h. p. single-phase motors are used can be obtained from the fact that several millions of new motors of this type are manufactured each year.

For operating machines or equipment requiring more than one h. p., it is seldom advisable to use single-phase motors if three-phase service is available, as the efficiency and power factor of single-phase machines is considerably lower than with three-phase motors. For a given horse power, a single-phase motor must be considerably larger than a three-phase motor of the same rating.

Approximate Currents taken by Standard Squirrel Cage Motors. (Full Load)

Size of Motor in H. P.	110 Volts			220 Volts			440 Volts			550 Volts			2200 Volts		
	1 Ph	2 Ph	3 Ph	1 Ph	2 Ph	3 Ph	1 Ph	2 Ph	3 Ph	1 Ph	2 Ph	3 Ph	1 Ph	2 Ph	3 Ph
⅙	3.34			167											
¼	4.8			24											
½	7.	4.3	5	35	2.2	2.5		1.1	1.3		.9	1.			
¾	9.4	4.7	5.4	4.7	2.4	2.8		1.2	1.4		1.0	1.1			
1	11.	5.7	6.6	5.5	2.9	3.3		1.4	1.7		1.2	1.3			
1½	15.2	7.7	9.4	7.6	4.	4.7		2	2.4		1.6	2.			
2	20	10.4	12	10	5	6		3	3		2.	2.4			
3	28			14	8	9		4	4.5		3	4			
5	46			23	13	15		7	7.5		6	6			
7½	68			34	19	22	17	9	11		7	9			
10	86			43	24	27	21.5	12	14		10	11			
15					33	38		16	19		13	15			
20					45	52		23	26		19	21			
25					55	64		28	32		22	26		6	7
30					67	77		34	39		27	31		7	8
40					88	101		44	51		35	40		9	10
50					108	125		54	63		43	50		11	13
60					129	149		65	75		52	60		13	15
75					156	180		78	90		62	72		16	19
100					212	246		106	123		85	98		22	25
125					268	310		134	155		108	124		27	32
150					311	360		155	180		124	144		31	36
200					415	480		208	240		166	195		43	49

Fig. 162. The above convenient table gives the approximate current per phase required by common squirrel-cage motors of different sizes and different voltages.

Single-phase motors are made in several different types, the most common of which are: **split-phase, repulsion, repulsion-induction,** and **series universal motors.**

Another type sometimes used is known as the **shaded-pole,** single-phase, induction motor.

Straight single-phase motors can be made with just one winding in the stator, and a few of the older type motors were made this way. A motor of this type will not start itself, but if it is started by hand or by some other method, it will develop torque due to the reaction between the stator flux and the flux of the current induced in the rotor once it is started to turn.

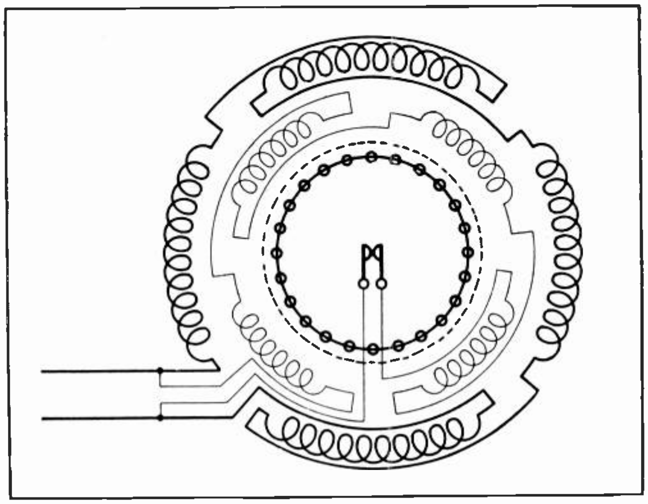

Fig. 163. This sketch shows the connections of the starting and running windings of a single-phase, split-phase A. C. motor.

175. SPLIT-PHASE, SINGLE-PHASE MOTORS

The split-phase principle is used to make single-phase motors self-starting and is in reality a simple method of obtaining a sort of polyphase winding and field.

One of the most common ways of obtaining this split-phase effect is by winding the stator with two sets of coils, the poles of which are displaced from each other by 90 electrical degrees. The main winding is known as the "running" winding, and the starting winding, which consists of fewer turns of smaller wire, is used only during the starting of the motor.

As soon as the motor is nearly up to speed, the starting winding is disconnected and cut out of service by a centrifugal switch, as explained in Articles 72 and 73 in Section Two of Armature Winding.

Fig. 163 shows a simple schematic diagram of a single-phase, split-phase induction motor. The running winding is shown by the heavy lines and the starting winding by the lighter lines. The squirrel-cage rotor is represented by the circular ends of the bars which are shown arranged in the circle in the center of the diagram and are all short-circuited together by a ring. The dotted circle represents the air-gap or division between the stationary and rotating members of the machine.

176. SPLIT-PHASE MOTOR PRINCIPLES

You will recall from the explanation given in Section Two of Armature Winding that the current which flows in the starting winding of a split-phase motor is considerably out of phase with that in the running winding, because of the different amounts of inductance and resistance in these two windings.

This causes the maximum current and flux to occur in these poles a fraction of a second earlier than in the poles of the running winding and produces a sort of shifting or rotating magnetic field around the stator. This rotating flux cuts across the bars or windings in the rotor and induces in them a heavy secondary current at low voltage.

The reaction between the stator flux and the flux of the rotor currents sets up the starting torque required to rotate the motor and bring it up to speed. After the rotor is turning at full speed the split-phase effect and starting winding are not necessary, as the normal reaction between the flux of the moving rotor conductors and the alternating flux of the stator will then maintain the running torque.

The centrifugal switches of motors of this type are arranged with weighted contacts or segments which are thrown apart by centrifugal force when the motor reaches full speed. The contacts of these switches are connected in series with the starting winding, as shown in Fig. 163; so they keep this winding open-circuited as long as the motor continues to run at full speed.

When the motor is stopped or slows down below a certain speed, the centrifugal force on the switch elements is reduced and a spring causes the contacts to again close and bring the starting winding back into service.

177. ROTOR CONSTRUCTION

Fig. 164 shows the squirrel-cage rotor of a small single-phase motor, and also the centrifugal switch which is attached to the plate on the right-hand end of the rotor. The copper bars of the rotor shown in this view are imbedded in slots in the laminated rotor core. The narrow openings of these slots can be noted in the figure.

The bars are, of course, too large to be inserted through these openings and are therefore inserted endwise through the slots. The end rings which short-circuit the bars to complete the closed circuits under each pole of the stator winding are shown fitted tightly to the sides of the laminated core. These end rings are securely attached to the bars by riveting the bar ends tightly into the holes in the rings or by brazing or soldering them in.

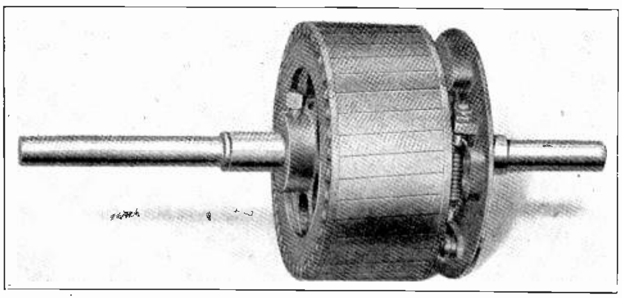

Fig. 164. Small squirrel-cage rotor such as used in single-phase induction motors. Note the centrifugal switch mechanism on the right end.

In some cases the squirrel-cage element complete, consisting of the bars and end rings, is cast from aluminum in one piece within the rotor core. On large squirrel-cage motors the bars are sometimes bolted or welded to the end rings.

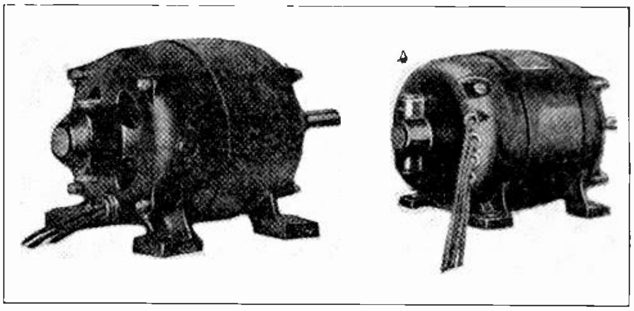

Fig. 165. Two small fractional h. p. A. C. motors of the single-phase, Split-phase type. There are millions of A. C. motors of approximately this size in use today.

The bars of squirrel-cage rotors are usually not insulated from the slots, as the copper or aluminum from which the bars are made is of so much lower resistance than the core iron that the low-voltage induced currents practically all flow through the bars, because they afford the easier path. In some cases, however, the rotor bars are insulated with a layer of stiff paper around them.

Fig. 165 shows two common types of single-phase split-phase motors of fractional h. p. size. Note the four leads which are brought out of each of these motors, two of which are the leads to the starting winding and two to the running winding.

To reverse a split-phase motor of this type it is necessary to reverse either the starting winding or the running winding leads. Some single-phase motors have their windings arranged so the coils can be connected either in series or parallel for operation on either 110 or 220 volts, and motors of this type also have four leads brought out of the frame.

The standard direction of rotation is clockwise when the motor is viewed from the end on which the pulley is placed or the end which has the shaft extension for the pulley.

178. CONDENSER TYPE SPLIT-PHASE MOTORS

The split-phase principle can be applied to single-phase motors by the use of a condenser or an inductance placed in series with one section of the stator winding. The leading or lagging current which is set up in the circuit by the condenser or inductance produces the separation or split-phase effect of the magnetic fields which occur in the different sections of the motor winding.

Figs. 166-A and B show two different methods used with split-phase motors of this type. These motors use a three-phase winding and depend upon the third wire from the condenser or inductance to supply current which is displaced in phase from that on either of the other two leads to the winding.

Another method which is quite often used with a later type of fractional h. p. single-phase motor is to use two windings displaced 90° from each other, one of which has a condenser connected in series with it. Both windings are left permanently connected to the line and the motor operates similarly to a two-phase motor.

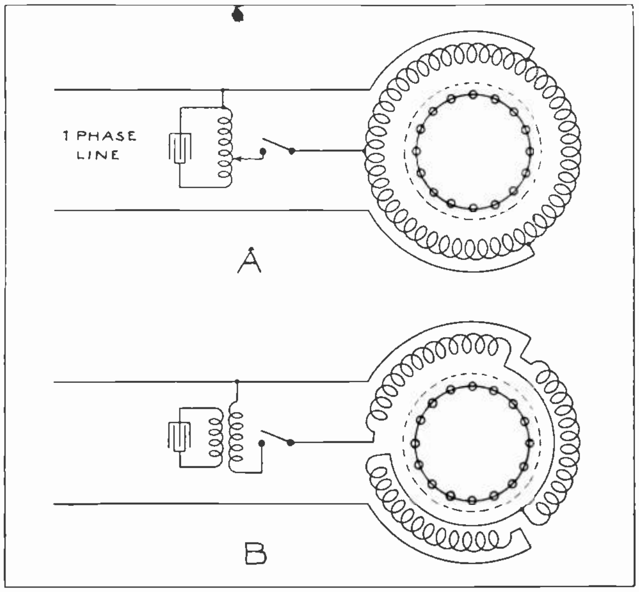

Fig. 166. The above two diagrams show the connections for two different types of single-phase, split-phase motors which use condensers and transformers to obtain the split phase currents for their stator windings.

This method entirely eliminates the use of the centrifugal switch. This is a particularly desirable feature, because the operation of motors equipped with centrifugal switches often causes considerable interference with radio receiving sets, when the motors of such devices as oil burners, refrigerators, and washing machines are started and stopped.

By using the proper size of condenser the lagging current effects produced by the motor windings can be neutralized to quite an extent by the leading current produced by the condenser. In this manner it is possible to obtain with these new single-phase motors, much higher power factor than the older types have.

Fig. 167 shows a condenser-type motor for single-phase operation. This motor uses a polyphase winding and has a regular squirrel-cage rotor, both of which can be clearly seen in this disassembled view. The condenser is shown completely enclosed in the metal box on the right.

179. SHADED-POLE MOTORS

Another method of producing torque in a single-phase A. C. motor is by the use of shaded poles similar to those explained under A. C. induction meters in Article 68 of Section Two on Alternating Current.

Fig. 168-A shows a diagram of a 6-pole, single-phase motor of the shaded-pole type, and at B is illustrated the manner in which the shading coil distorts the magnetic flux of the main pole.

The shading coil consists of a small coil of a few turns of wire wound into a slot and around one side of the main pole. This coil is short-circuited, so that it always forms a complete circuit and acts as a secondary winding, receiving induced current from the flux of the main pole winding.

When the main winding is excited with A. C. it sets up a powerful alternating magnetic field which induces current in the rotor bars and also in the short-circuited shading coil. The induced current in the shading coil sets up a flux approximately 90° out of phase with that of the main winding.

The flux set up by the shading coil will therefore distort the flux of the main pole as shown at B in Fig. 168.

The reaction between these two magnetic fields which are out of phase with each other causes a

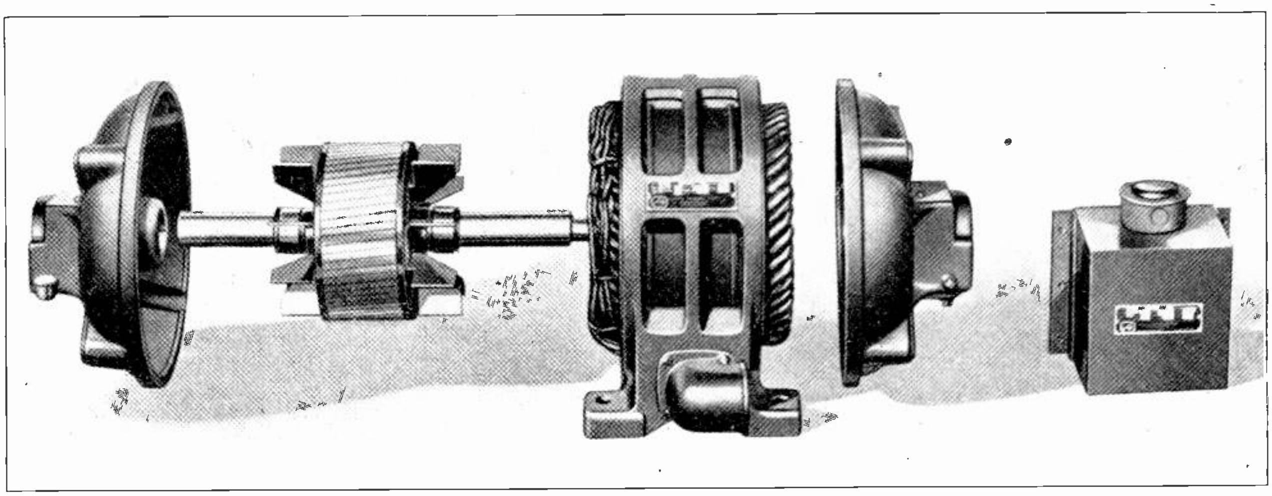

Fig. 167. This photo shows an excellent disassembled view of a squirrel-cage induction motor for single-phase operation and also the condenser by which it obtains the split phase currents for its stator winding.

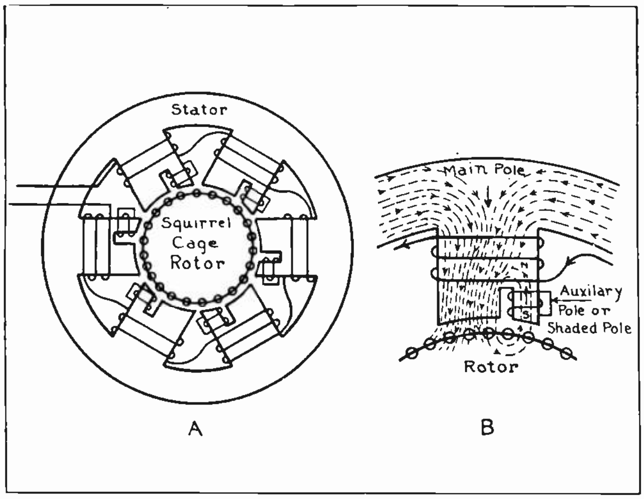

Fig. 168. The above two sketches show the construction and illustrate the principles of the shaded-pole type induction motor.

shifting flux across the face of the main poles, which produces a sort of rotating field effect.

This shifting or rotating field from the shaded stator poles reacts with the flux of the induced current in the rotor and sets up the torque required to operate the motor.

Motors of this type are self-starting and do not require any centrifugal switches or other circuit-breaking devices. They can be reversed by changing ends with the stator, that is by removing the stator, changing it end for end, and replacing it in the frame.

Shaded-pole motors are used in some electrical fans and for certain other devices requiring fractional horse power motors, but they are not used very often in larger sizes because of their rather low power factor and efficiency.

180. REPULSION MOTORS

Another type of single-phase motor very commonly used is the **repulsion** motor. This motor doesn't operate on the split-phase principle but obtains its torque by repulsion between definite poles induced in the rotor and the poles set up in the stator by the current supplied from the line.

Fig. 169 shows a simple diagram of a single-phase repulsion motor. The stator of this machine has only one winding, which is excited by alternating current from the line and sets up an alternating field or reversing magnetic poles in the stator.

The rotor, which is represented by the symbol for the commutator in Fig. 169, has a wire winding of the wave type similar to that used in D. C. motors. The brushes which rest on the commutator are short-circuited together so they form complete circuits through various sections of the armature winding.

The alternating flux set up by the stator winding induces secondary currents in the rotor or armature winding, and these currents flowing through the paths created by the commutator bars and shorted brushes set up definite alternating poles at certain points on the rotor.

Only two brushes are required with ordinary wave windings but four brushes are quite commonly used on motors of four poles. The two small sketches at the right in Fig. 169 show different methods of connecting the brushes for short-circuiting them together. In some cases the brushes are simply grounded to the frames or to a metal ring, as illustrated in the lower small sketch at the right in this figure.

The great majority of repulsion motors are made in the four-pole type, but a few of the two-pole and six-pole type are also made.

181. OPERATING PRINCIPLE

The location of the poles set up by the induced current in the rotor will depend upon the position in which the brushes are set. These brushes are located so that the centers of the induced rotor poles will be built up at a point a few electrical degrees to one side or the other of the center of the stator poles; and so that the polarity of the induced poles in the rotor will be the same as the polarity of the nearby stator pole.

The magnetic repulsion which takes place between these like poles which are only a few degrees apart from each other, will exert a strong turning force on the rotor and thus develop the torque required to operate the motor.

By shifting the brushes a short distance, the induced rotor pole can be set up on the opposite side of the stator pole and thus cause the motor to reverse its direction of rotation.

The speed of repulsion motors can also be varied widely by shifting the brushes so that the rotor poles are induced at a point closer to or farther away from the stator poles.

Repulsion motors produce very good starting torque and have fair efficiency and power factor.

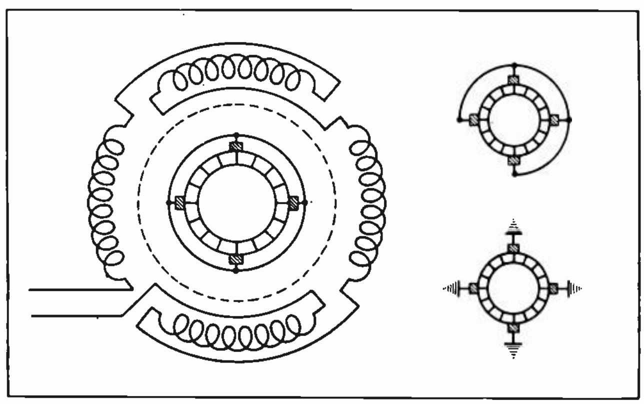

Fig. 169. This diagram shows the connections of the stator winding and brushes of a single-phase A. C. repulsion motor.

182. COMPENSATING WINDINGS

In some cases they are equipped with an auxiliary winding which is connected to an extra set of brushes and is known as a **compensating winding.** Fig. 170 shows the connections for the compensating winding of a motor of this type. The compensating winding is the one shown in lighter lines and is connected to brushes B and B-1. Brushes A and A-1 are the main brushes which short-circuit the proper sections of the rotor winding to produce the regular motor torque.

The purpose of this compensating winding is to improve the power factor and stabilize the speed of the repulsion motor.

Repulsion motors are commonly made in sizes from fractional h. p. to 10 h. p. They, of course, have the disadvantage of requiring a commutator and brushes, which add extra wearing parts to the motor and at times cause a certain amount of sparking if they are not properly cared for.

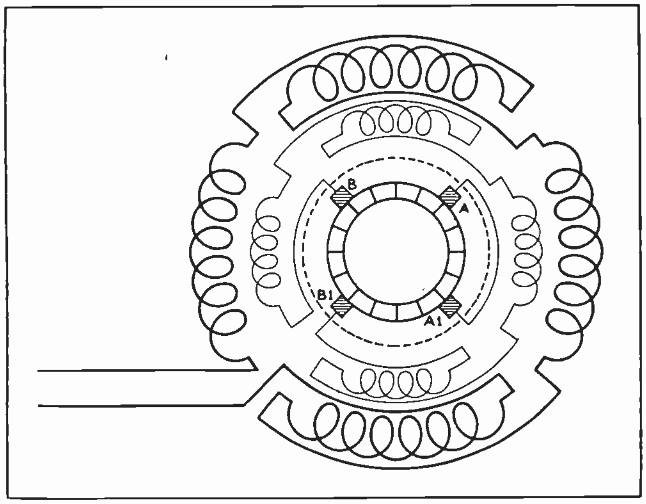

Fig. 170. Diagram of the connections for a repulsion motor with a compensating winding which improves the power factor of this type of machine.

Fig. 171 shows a disassembled view of a single-phase repulsion motor. Note the single-phase winding in the stator core and the typical D. C. armature winding on the rotor. The other parts shown are the end shields, bearing sleeves, rings, brush holders and ring, end-bracket bolts, brushes, and the rails upon which the motor frame is mounted for belt tightening adjustment.

183. REPULSION-INDUCTION MOTORS

Single - phase repulsion - induction motors are simply a combination of the repulsion and induction motor principles. A motor of this type starts as a repulsion motor and runs as an induction motor; thus, the name, **repulsion-induction** motor.

These motors have one winding in the stator and a wire-wound armature equipped with a commutator and brushes as shown in Fig. 172. During starting, the brushes rest on the commutator, thus short-circuiting only certain sections of the rotor winding, setting up like poles near the stator poles, and causing the repulsion torque, the same as the straight repulsion motor.

When the motor reaches nearly full speed a centrifugal device, shown at "A" in Fig. 172, short-circuits all the bars of the commutator together, thus shorting the entire rotor winding and making it act similarly to a squirrel-cage winding.

In some cases the centrifugal device also lifts the starting brushes off the commutator to reduce the wear on the commutator and brushes while the machine is running normally.

After the commutator is shorted, the machine runs as an ordinary single-phase induction motor. In this manner, good starting torque and moderate starting current of the repulsion motor are obtained during starting of the load, and the motor when running operates with the constant speed characteristics of an induction motor.

By equipping these motors with a compensating winding, their power factor can be kept very high when operating at full speeds. Repulsion-induction motors will develop from 2½ to 5 times full load torque during starting and require only from about 2 to 2½ times full load current for starting.

184. SERIES OR UNIVERSAL A. C. MOTORS

If a motor has a wire-wound armature and a commutator of the D. C. type connected in series with its stator winding as shown in Fig. 173, and is then connected to a single-phase A. C. line, the motor will operate very much the same as a series D. C. motor. This is due to the fact that when the armature and stator are connected in series, the alternating current reverses in both of these windings at the same time, and causes the magnetic poles set up in the rotor and stator to also reverse at the same time, and thereby retain a fixed relation to each other at all times.

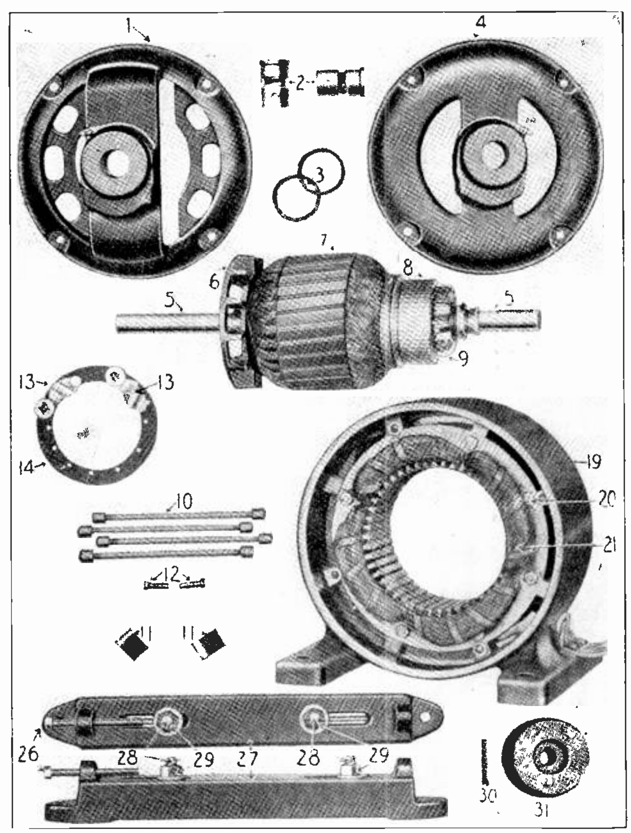

Fig. 171. Disassembled view showing important parts of an A. C. single-phase repulsion motor.

As an illustration: We know that if we reverse both the armature and field leads of a shunt D. C. motor, the machine will continue to operate in the same direction; so we can see that if the polarity of both the armature and field are reversed continually but always at the same time, the motor will continue to develop torque in one direction.

Small ordinary D. C. motors can be operated in this manner on single-phase alternating current, provided the field poles are of laminated construction so they don't overheat due to eddy currents when alternating current is applied.

It is because of the fact that this type of motor can be operated either on direct current or alternating current that it is very commonly called a **universal** motor.

A great many small, fractional horse power, universal motors are made for use with electric fans, household appliances, dentists' tools, and other equipment which may have to be changed from D. C. circuits to A. C. circuits.

The characteristics of series A. C. motors are very similar to those of D. C. series motors. The A. C. series motor will produce excellent starting torque but has very poor speed regulation.

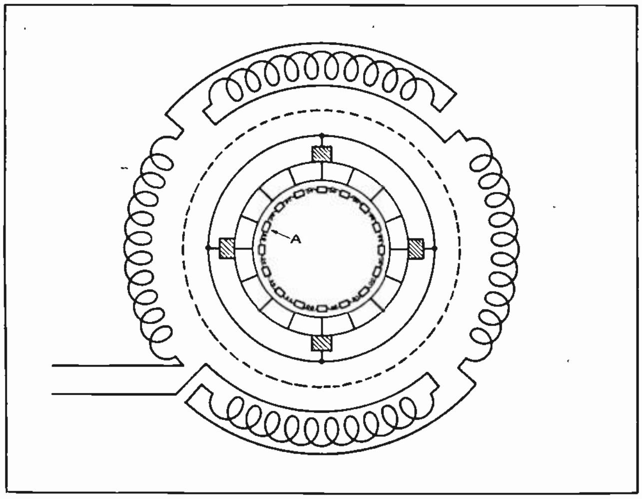

Fig. 172. This diagram shows the connections and arrangement of the short-circuiting device of a repulsion-induction motor. The short-circuiting mechanism at "A" lays around the inside of the commutator bars and short-circuits them all together when the machine comes up to speed.

The speed of these motors can be varied either by connecting a rheostat in series with them or by varying the applied voltage with an auto transformer.

Series A. C. motors of large sizes are quite commonly used in traction service on electrically-operated railway cars and locomotives.

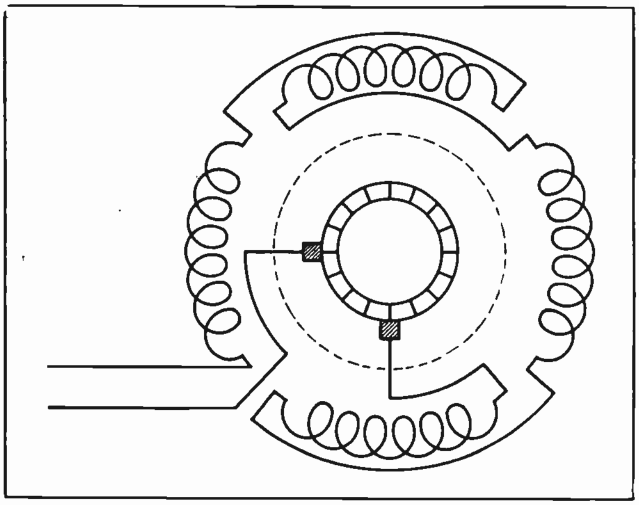

Fig. 173. Stator and armature connections for a series A. C. motor of the universal type which can be operated on either D. C. or A. C.

Besides having the necessary starting torque and speed variation range which are ideal for railway work, these motors possess the added advantage of being able to operate on either D. C. or A. C. trolleys.

For example, the New York, New Haven & Hartford Railroad have been using motors of this type for many years. Their trains are operated on alternating current when outside of New York City, and when within the city they operate from direct current.

185. STARTING SINGLE-PHASE MOTORS

Single-phase motors of fractional h. p. and those up to 2 h. p. are commonly started by connecting them directly across the line. Snap switches are generally used for starting those under ½ h. p., and small knife-switches of the enclosed safety type are used for starting those over ½ h. p.

Single-phase motors of 2 h. p. to 10 h. p. are often started with a simple starting-box of the resistance or inductance type, to reduce the starting voltage and prevent too heavy surges of starting current.

The use of starting boxes is particularly desirable where the motors are operated from circuits to which lights are connected, as otherwise the heavy starting currents may cause objectionable voltage drop and dimming of the lights.

Where the motors are operated from power circuits, even the largest single-phase motors are sometimes started directly across the line.

POLYPHASE A. C. MOTORS

Polyphase A. C. motors are the most extensively used of any form of power device. They are made in a wide range of sizes from ½ h. p. up to thousands of h. p. each, and are designed to operate at speeds from less than 100 R.P.M. to 3600 R.P.M. on 60 cycles.

Polyphase motors are self-starting without the aid of auxiliary windings or centrifugal switches. The most commonly used type of polyphase motor has no commutator or brushes, and therefore has very few wearing parts and produces no sparking hazard.

Polyphase motors can be obtained to fit practically any class of drive or power need, and these are by far the most common type motor used for large power equipment. Fig. 174 shows a modern polyphase induction motor.

There are three general types of polyphase motors, known as: **squirrel-cage induction** motors, **slip ring** or **phase-wound induction** motors, and **synchronous** motors.

Any of these types can be obtained for either two or three-phase operation, but two-phase motors are not very extensively used any more.

186. OPERATING PRINCIPLES

The operating principles of both two and three-phase motors were explained and illustrated, Articles 74 and 75 of Section Two of Armature Winding, and before proceeding farther with this section you should carefully review these articles and Figs. 56 and 57 of Section Two on Armature Winding.

You will recall that the stator winding of a polyphase motor sets up a revolving magnetic field, which induces secondary currents in the rotor winding or bars. The reaction between the flux of the stator winding and the flux of this rotor current causes a smooth and powerful torque which turns the rotor.

By reviewing Article 74 of Section Two of Armature Winding, you will find that two-phase motors have two windings which are displaced 90 electrical degrees from each other in the stator core.

A simple method of representing the windings of a two-phase motor in electrical diagrams is shown in Fig. 175. The two small sketches in Fig. 175-B show the two-phase "mesh" or delta connection above, and the two-phase star connection below.

When two-phase motors are equipped with wound rotors, regular three-phase wound rotors are generally used. This eliminates the need for four collector rings, and the three-phase rotor winding works equally well on the induced current which it receives from the rotating magnetic field of the stator.

When the stator windings shown in Fig. 175-A are supplied with two-phase current, a rotating field is set up, as explained in Article 74, Section Two of Armature Winding. This rotating magnetic field will induce secondary currents in the squirrel-cage, or in wound rotor, whichever is used; and the reaction between the flux of the rotor currents and that of the stator field produces the motor torque.

The same squirrel-cage rotor can be used in either a two-phase or three-phase motor, provided they both have the same diameter of stator core opening.

Two-phase motors can be reversed by reversing the leads of either phase.

187. THREE-PHASE MOTORS

As three-phase energy is so convenient and economical for power transmission purposes and as it is also ideal for producing a uniform revolving field in polyphase motors, three-phase motors are by far the most commonly used of any type of electric motor for the heavier power needs.

In Section Two on Armature Winding we learned that the stators of three-phase motors have a uniform and continuous winding, to which the line leads are connected 120 electrical degrees apart.

Review carefully the manner in which these windings are arranged and connected for obtaining different numbers of poles, and also the manner in

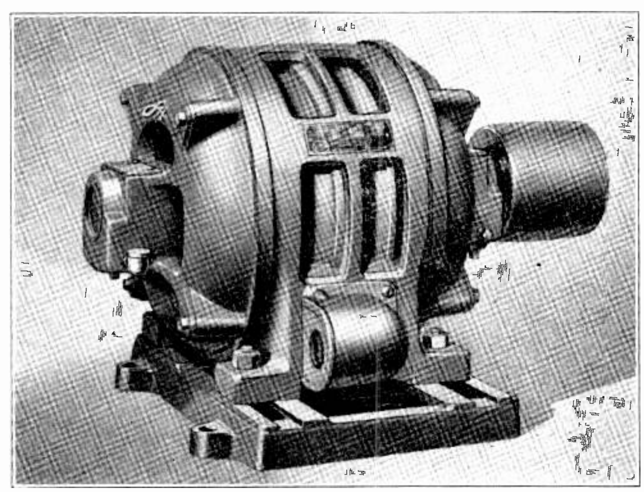

Fig. 174. This photo shows a modern polyphase induction motor. The three phase leads from the line are connected to the stator leads in the connector box shown on the side of the frame.

which they set up the revolving magnetic field when the stator is supplied with three-phase energy.

It is easy to see that this revolving field will cut across the bars of a squirrel-cage rotor, or across the conductors of a phase-wound rotor, and induce in them the secondary currents which, by the reaction of their flux with the flux of the stator, produce the motor torque.

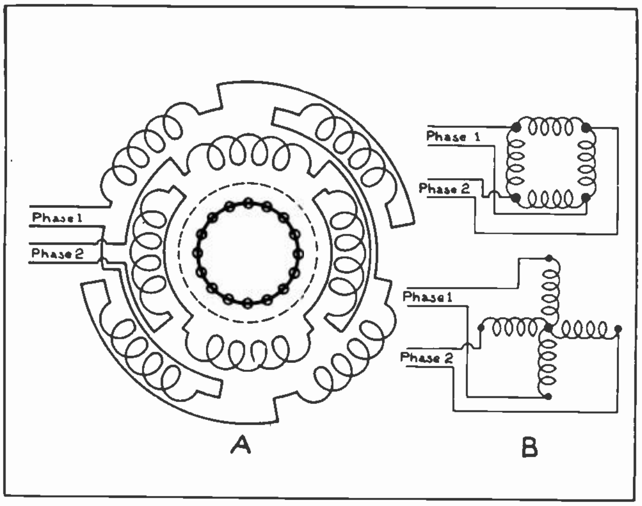

Fig. 175. A. This diagram shows the connections of the stator windings of a two-phase induction motor. At B are shown two schematic diagrams illustrating different methods of connecting two phase windings.

Fig. 176 shows two excellent cut-away views of a modern three-phase squirrel-cage induction motor. This figure shows clearly the important constructional features and the location of all the parts in the assembled motor. Note carefully all details of the construction of the rotor, stator, windings, frame, bearings, ventilating openings, etc.

The windings of a three-phase motor can be represented in simple schematic diagrams as shown in Fig. 177-A or B, according to whether they are connected delta or star.

As three-phase motors are so extensively used, the following discussion of characteristics of the various types of motors will refer principally to three-phase machines. Many of the same characteristics are, however, also found in two-phase motors.

188. SQUIRREL-CAGE MOTOR CHARACTERISTICS

Squirrel-cage motors are commonly referred to as constant speed motors; but their speed is not quite constant, as they do not operate at synchronous speed and their "slip" varies with the amount of load applied to them.

When a squirrel-cage motor is not loaded, its speed will be very near to that of the revolving magnetic field, or synchronous speed. As load is applied to the motor, its speed is gradually reduced until at full load the slip is usually from 3 to 5 per cent. on large motors, and may be as much as 8 or 10 per cent. on small single-phase machines.

The full load torque of a squirrel-cage motor of any given size is the same as that of a slip-ring or synchronous motor of the same size; because the full load torque, you will recall, depends entirely

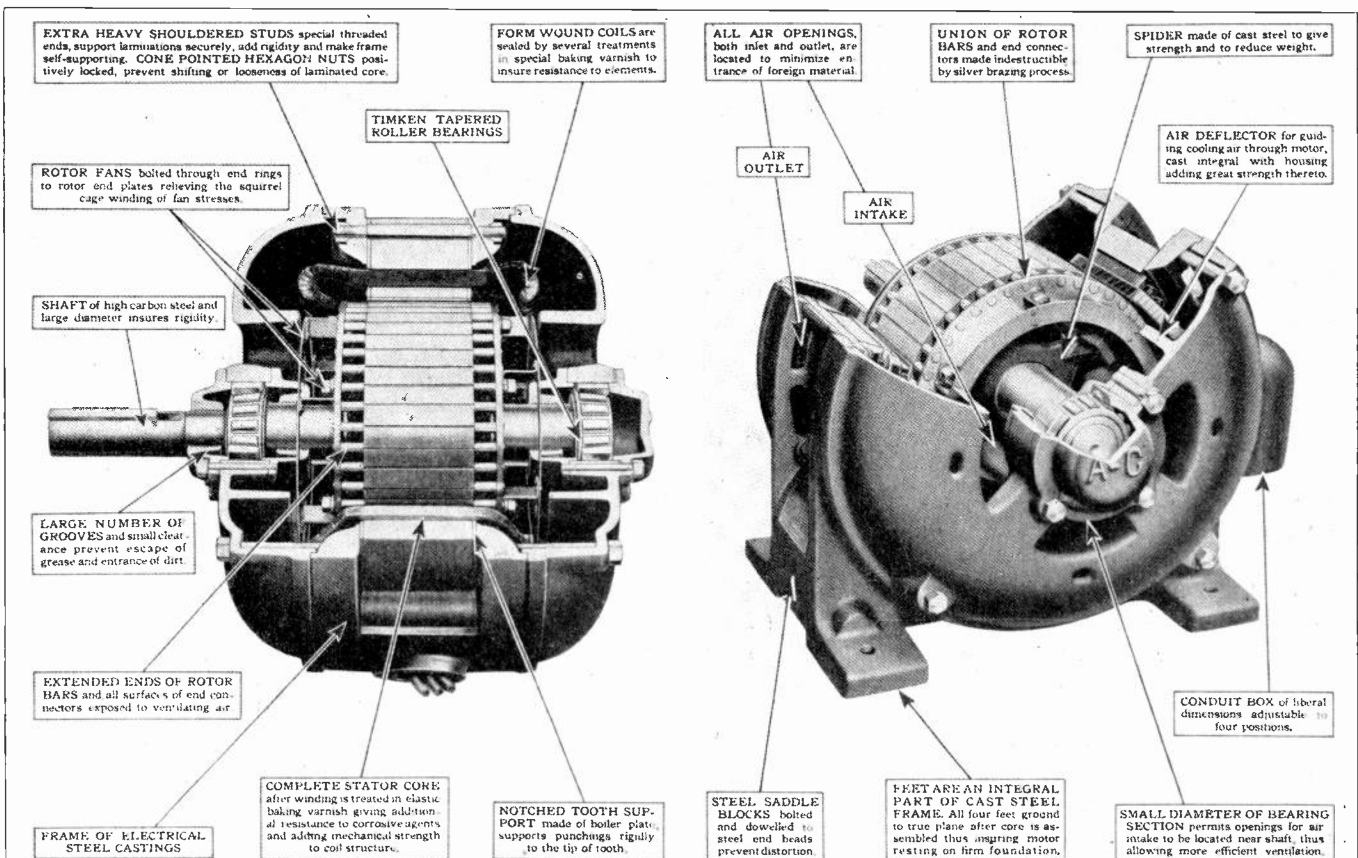

Fig. 176. The above photo shows two cut-away views of a polyphase squirrel-cage induction motor. The important parts of the motor are clearly shown in these two views and you should carefully note the descriptions given for each part. A careful study of this figure will show a number of very important features of induction motor construction. (Photo courtesy Allis-Chalmers Mfg. Co.)

upon the speed and horse power rating for which the motor is designed.

The load pull-out torque of the squirrel-cage motor should not be less than 150% of the full load torque, and with certain types of motors it will be as high as 250% of the full load torque.

Having a pull-out torque considerably greater than the full load torque enables the motor to carry momentary overloads without stalling.

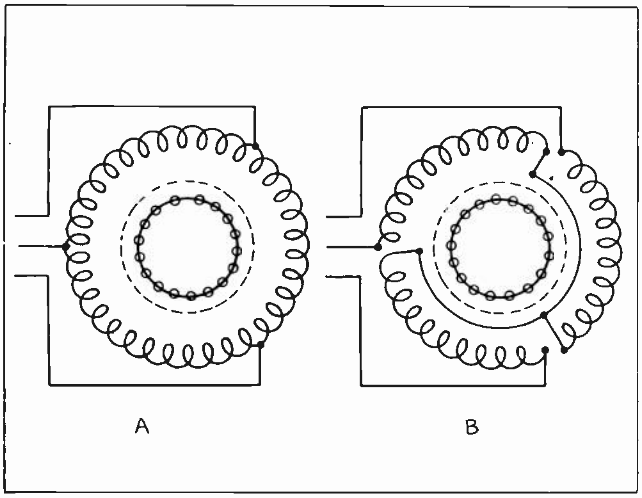

Fig. 177. A shows a delta-connected stator winding for an induction motor. The sketch at B shows a star-connected winding.

189. STARTING TORQUE

The starting torque of squirrel-cage motors depends upon the design of the rotor and upon the value of the voltage applied to the stator winding during the starting period.

A very important rule to keep in mind when working with induction motors is as follows: **the starting torque of an induction motor varies with the square of the applied voltage.**

Good starting torque can be obtained with squirrel-cage motors by starting them on the full line-voltage or the rated voltage of the machine. When started in this manner, the current taken by the motor will be several times the normal full load current; and if heavy loads are being started, the starting current may range from 4 to 9 times full load current.

If the load should require considerable time to come up to speed, the heavy starting current required during this time may overheat and possibly damage the stator windings. For this reason the type of load to be started must be taken into consideration when determining the starting voltage to be applied to the motor.

The very heavy surge of starting current which results when squirrel-cage motors are started at full line-voltage is often very objectionable, as it causes voltage drop in the line and this voltage drop may interfere with the operation of other power equipment or cause considerable variation in the brilliancy of lights that may be attached to the same circuit.

In some cases the supply lines may not be large enough to permit the starting of induction motors on full line-voltage. In many cases power companies object to or do not permit this method of starting motors which are connected to their lines. So, for these reasons, many squirrel-cage motors of 5 horse power and larger are started at reduced voltage by the use of some form of motor-starting devices.

A. C. motor starters are explained in a later section. Their principal function, however, is to reduce the voltage to the motor by means of resistance or inductance in the circuit of the stator winding during the starting period. When the starting voltage is reduced, the heavy surge of starting current will also be greatly reduced and, of course, the starting torque developed by the motor will also be considerably lower.

The convenient table in Fig. 178 shows the effect which reduced starting voltage has on the starting current and starting torque of common induction motors. The various starting voltages shown in the table range from 33% to 100% of the rated motor voltage, and the starting current and starting torque for each different voltage are given in percentage of full-load current and full-load torque of the machine.

Some induction motors are designed with special squirrel-cage rotors to improve the starting torque. These machines will be explained in later paragraphs.

Fig. 178-A gives a set of curves which show the starting torque and starting current of a typical squirrel-cage motor. Curve A shows the starting torque on full line voltage, and curve A-1 shows the starting current for the same condition. Curves B and B-1 show the starting torque and current of a squirrel-cage motor with a high resistance rotor. Note how the added resistance increases the torque and decreases the current.

Curves C and C-1 show the starting torque and current when a starting compensator is used with an ordinary squirrel-cage motor. Note how the torque at reduced stator voltage is lower than with

Starting voltage in percent of rated motor voltage	Starting current in percent of full load current	Starting torque in percent of full load torque
33%	75%	22 %
40 "	110 "	33.3 "
50 "	175 "	50 "
60 "	250 "	70 "
66 "	300 "	88 "
80 "	450 "	130 "
100 "	700 "	200 "

Fig. 178. The above table shows the effect of reduced starting voltage on both the starting current and starting torque of induction motors.

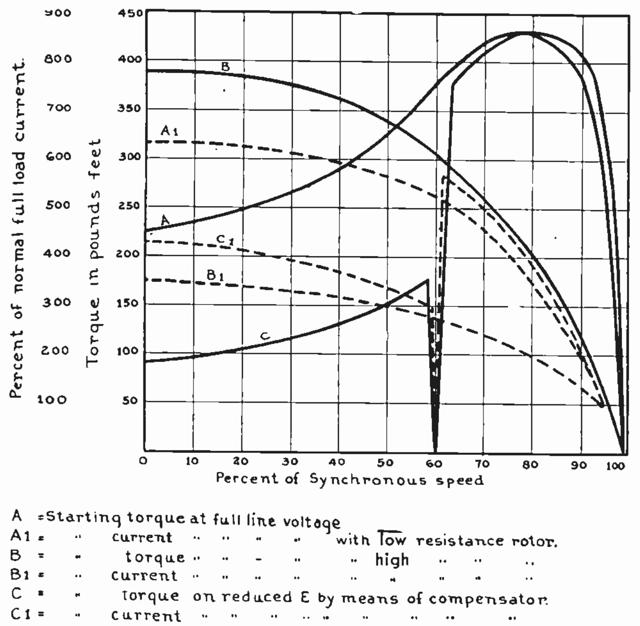

Fig. 178-A. The above diagram shows voltage, current, and torque curves of an ordinary squirrel-cage motor. A careful study of these curves will help you gain an understanding of these very important characteristics of squirrel-cage motors.

either of the other methods of starting, and also the interruption and sudden increase of torque when the compensator switches over to full voltage.

190. POWER FACTOR AND EFFICIENCY

The power factor of three-phase, squirrel-cage motors operated at full load may vary from 60 to 70 per cent. in the case of small low speed motors, to 75 to 90 per cent. for medium-sized motors; and as high as 90 to 96 per cent. for large motors of several hundred horse power and up.

Power factor is a very important characteristic to be considered when selecting large induction motors or a large number of small ones; because, as explained in an earlier section, a great deal of money can be saved on power bills by keeping the power factor of the system as high as possible.

It is also very important to remember that any induction motor operates at a much lower power factor when it is lightly loaded, and for this reason motors should be properly chosen so that during normal operation they will be running at or near full load a greater part of the time.

The efficiency of squirrel-cage motors varies similarly to the power factor. Small low-speed motors may have efficiencies ranging from 50 to 80 per cent., while the larger machines will operate at efficiencies from 90 to 95 per cent.

The efficiencies are usually best when the motors are operating above 75% of their full rated load. High-speed motors of the two and four-pole type generally have the highest efficiency and power factor.

Fig. 178-B shows the power factor and efficiency curves for a 100 h. p. squirrel-cage motor. Note that the P.F. and efficiency are both very low at light loads, under 20 h. p., and then rapidly rise to high values on loads between 60 and 100 h. p., but fall off again when the motor becomes overloaded. This figure also shows the current and speed curves of the motor at various loads.

191. FACTORS CONTROLLING SPEED OF INDUCTION MOTORS

As explained in the earlier part of this section, the speed of induction motors depends upon the number of poles in the stator winding and upon the frequency of the alternating current on which they are operated.

As induction motors are designed to operate on practically constant frequency, their speed should not be varied to any appreciable extent by varying the frequency.

The speed of squirrel-cage induction motors can be changed by changing the number of poles in the stator winding, as explained in Section Two of Armature Winding. If the speed change is to be permanent, the stator can be reconnected for a different number of poles; while, if it is desired to frequently make a certain change in the speed during operation of the motor, the stator winding can have the pole leads brought out separately to terminals of a switching device by means of which the number of poles can be quickly changed by regrouping them. The switching device and connections for this method of varying the speed of squirrel-cage motors will be explained in a later section on A. C. Motor Controls.

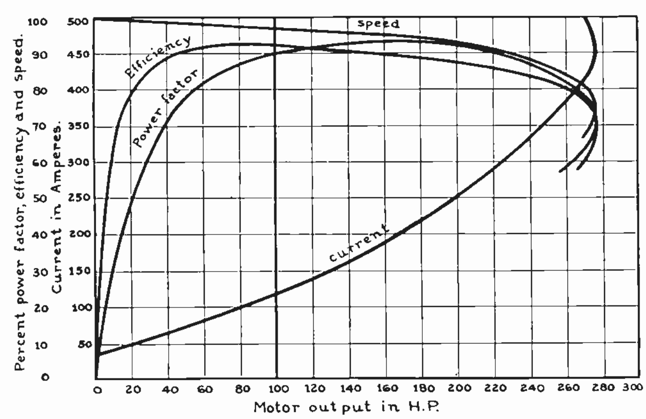

Fig. 178-B. This diagram shows the efficiency, power factor, speed, and current curves for a 100-h. p., squirrel-cage motor. Note carefully how the efficiency and power factor vary with different amounts of load up to full rated load, and also on various overloads.

The direction of rotation of a three-phase induction motor can be reversed by reversing any two of the three-phase leads to the motor.

192. GENERAL APPLICATION

Because of their very rugged construction and small number of wearing parts, squirrel-cage induction motors find a very wide field of application. They require very little maintenance and repair, if they are operated under the proper conditions.

Having no commutator brushes or other sliding contacts they do not produce any sparking and can therefore be used in many locations where other types of motors cannot be used because of the danger of explosions. This applies to buildings or locations where explosive gases or dust may be in the air.

When selecting and installing motors it is well to keep in mind that sawdust, coal dust, starch, flour, grain dust of any kind, sugar, etc., are very explosive when mixed with air in just the right proportions. This is also true of paint and varnish fumes, oil vapors, and vapors from certain chemicals.

To eliminate fire and explosion hazard, squirrel-cage motors are invariably used in modern plants manufacturing or handling materials such as those just mentioned. Fig. 179 shows a number of squirrel-cage motors of various sizes, and Fig. 180 shows a 100-h. p. squirrel-cage motor installed in a cotton gin plant.

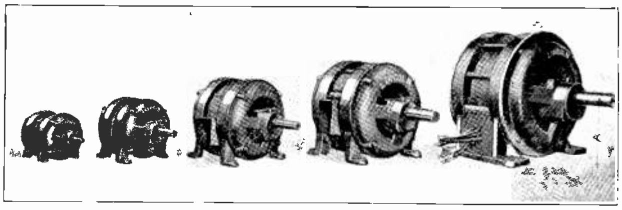

Fig. 179. This photo shows a group of polyphase induction motors of various sizes. Motors of this type are available in practically any size required.

Some of the uses to which squirrel-cage induction motors are commonly put are as follows:

- Machine drives in industrial plants
- Machine drives in wood-working plants
- Operating machines in general manufacturing plants
- Textile mill drives
- Saw mills
- Paper mills
- Steel mills
- Grain elevators
- Flour mills
- Mining machinery
- Electric ship propulsion
- Passenger and freight elevators
- Motor-generator sets
- Small hoists
- Pumps and fans

193. SLIP-RING MOTORS

From the foregoing material on squirrel-cage motors, it is evident that they are not well adapted to variable speed service. Where variable speed duty is required, slip-ring induction motors are commonly used.

These slip-ring or phase-wound motors have stators and stator windings of exactly the same type as those used in squirrel-cage motors, but their

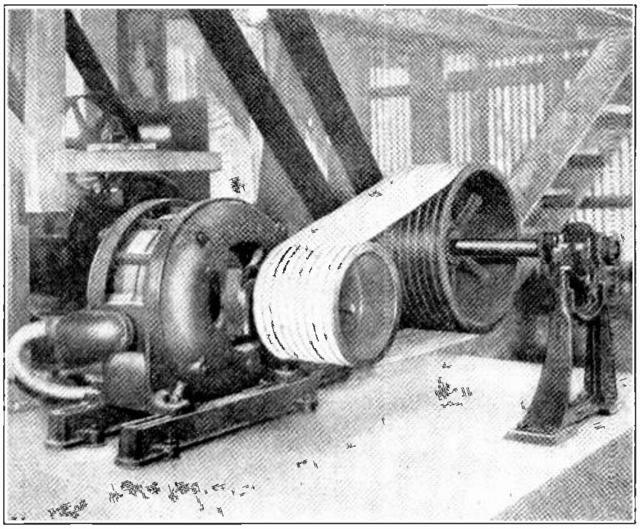

Fig. 180. This photo shows a 100-h. p. squirrel-cage motor driving machinery in a cotton mill. The motor operates the large pulley on the line shaft by means of the "texrope" drive, and belts convey the power from this shaft to the driving machinery. (Photo courtesy Allis-Chalmers Mfg. Co.)

rotor windings are made of insulated copper wire or bars somewhat similar to those used on direct current machines.

Generally these rotors are wave-wound and star-connected, although in some cases they are lap-wound and delta-connected. The star-connected wave-winding is somewhat easier to install and produces better mechanical strength and balance of the rotor.

Three leads are connected to the rotor winding at points 120 electrical degrees apart and are brought out along the shaft and connected to three slip rings.

Fig. 181 shows a wound rotor of a slip-ring motor and the slip rings can be clearly seen mounted on the shaft. These rings are usually made of brass and are well insulated from each other and from the shaft. This rotor in Fig. 181 has a winding of insulated copper wire.

Fig. 181-A shows another phase-wound rotor which has a winding of insulated copper bars, which are properly connected to the slip rings on the shaft.

During operation of slip-ring motors the brushes slide on the rings and provide a connection for the

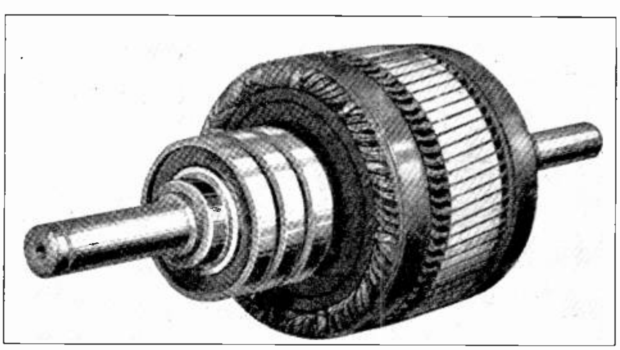

Fig. 181. Wound rotor of a variable speed slip-ring motor. This rotor has windings of insulated copper wire similar to those in D. C. armatures.

induced currents to flow from the rotor winding to a control resistance in the external circuit. By varying this resistance the secondary current flow in the rotor can be varied; and this will increase or decrease the amount of torque and slip, and thus vary the speed of the motor.

Controllers of the face-plate type or drum type are commonly used with variable speed, slip-ring motors.

Fig. 182 shows a 440-volt induction motor of the slip-ring type. Note the brushes resting on the three slip rings and also note the three leads which are brought out from these brushes for connection to the controller by which the speed of the motor is varied.

The connections of the stator winding are made at the hooded outlet shown on the side of the motor frame. The slots shown between the sections of the laminated stator core of this motor are provided for the circulation of cooling air.

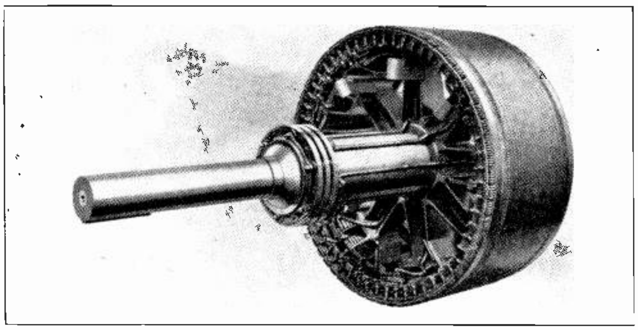

Fig. 181-A. Phase wound rotor of a large slip-ring induction motor. This rotor has heavy bar windings which are not shorted together like those of a squirrel-cage rotor, but instead have connections brought out from each phase to the slip rings.

194. STARTING AND SPEED CONTROL WITH EXTERNAL RESISTANCE

Fig. 183 shows a schematic diagram of the connections for the stator, rotor, and starting or speed-control resistance of a slip-ring motor. The resistance is shown connected star, the same as the rotor windings, and if you trace the circuit from each section of the rotor winding you will find that the complete resistance of two sections of the controller is in series with it.

The three sliding-contact arms which are indicated by the arrows are connected together at the central point and are arranged to cut out this resistance as they are rotated in a clockwise direction.

This resistance is used for starting slip-ring motors as well as for controlling their speed, and if the amount of resistance is properly proportioned these motors have a very good starting torque with moderate starting currents.

Before starting the motor by closing the line switch, the controller should be set so that the maximum amount of resistance is in the rotor circuit. Then this resistance is gradually cut out as the motor comes up to speed.

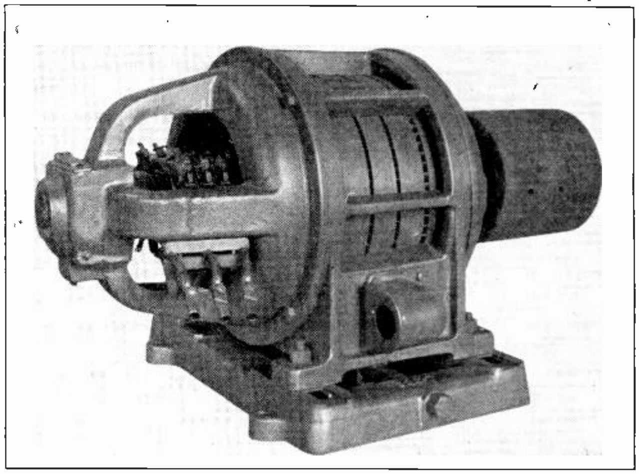

Fig. 182. This photo shows a complete slip-ring motor to which variable resistance can be connected for starting and speed-regulating duty. Note the slip rings and rotor connections on the left-hand end of the machine. (Photo courtesy General Electric Co.)

In many cases slip-ring motors with resistance starters are used just because of their good starting torque and lower starting currents, even though they may not be required to give variable speed service.

If the resistance is only used for starting duty it can be much smaller and lighter than when used for speed-regulating duty. When used for regulating the speed of the motor the rheostat must have resistance elements large enough to carry the full load current continuously without overheating.

After the motor is up to speed, if resistance is again cut into the rotor circuit, the speed will be decreased in proportion to the amount of resistance inserted.

Fig. 184 shows a diagram of a heavy-duty slip-ring motor with the starting and speed regulating resistance arranged so it can be cut in or out of the rotor circuit by means of short-circuiting switches.

The motor is started with all of the resistance switches open and the full resistance in the rotor circuit. When switch No. 1 is closed it shorts out the first section of resistance; switch 2 shorts the second section, and switch 3 shorts out the last of

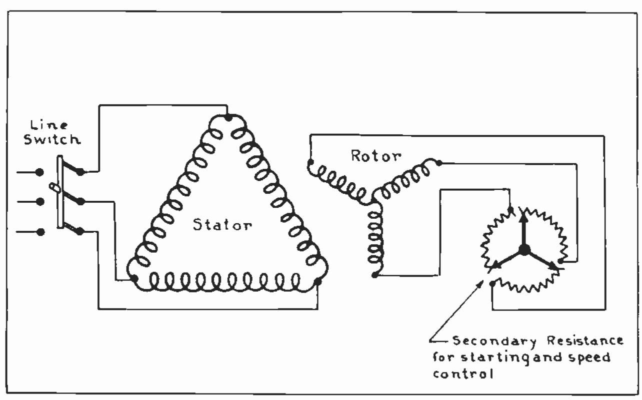

Fig. 183. The above diagram shows the connections of the stator and rotor of a slip-ring induction motor, and also the variable resistance used in the rotor circuit for starting and speed control.

the resistance, bringing the motor up to full speed.

For starting and controlling the speed of large motors of this type magnetically operated contactors or breakers are used in place of the knife switches shown in Fig. 184.

The value of the induced voltage in the secondary or rotor winding of a slip-ring motor may vary between 25 and 60 per cent. of the stator voltage, according to the design of the motor.

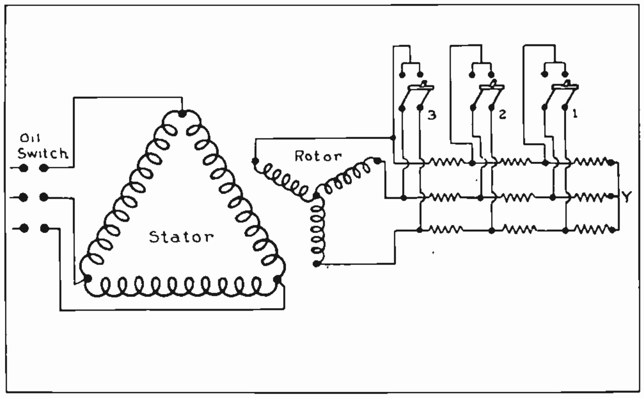

Fig. 184. Connection diagram of slip-ring induction motor with knife switches used to cut out the starting or speed control resistance step by step.

195. INTERNAL RESISTANCE MOTORS

On small motors with phase-wound rotors the secondary resistance is often mounted in the rotor spider so that it revolves with the rotor winding and can be connected directly to it, thus eliminating the necessity for collector rings and brushes.

In such motors the resistance may be cut out or short-circuited by a centrifugal switch as the motor comes up to speed. In other cases motors of this type are equipped with a hollow shaft, through which a rod is run and connected to the mechanism which operates the contacts to cut the rotor resistance in or out of the circuit.

This rod is provided with a knob on the outer end and can be pushed back and forth by hand while the motor is operating. Motors of this type with the internal secondary resistance should not be used on loads which require too great a length of time to come up to speed, or the resistance units may be damaged by overheating.

Motors with internal rotor resistance are usually not made in sizes over 20 h. p. Motors larger than this are practically always equipped with slip rings and external resistance and many of the smaller slip-ring motors also have external resistance.

196. CHARACTERISTICS OF SLIP-RING MOTORS

Slip-ring motors can be designed to give a starting torque of 250% or more of the full load torque. A starting torque of 125% may be obtained with a stator current of 150% of full load current rating; and a starting torque of 200% can be obtained with 250% of full load current, etc.

This ability to produce good starting torque with moderate starting currents makes the slip-ring motor very desirable where loads must be frequently started and stopped, and where it is necessary to avoid heavy starting current surges of 4 to 6 times the running current value.

Figs. 185-A and B give a set of curves which show the starting torque and starting current of a slip-ring motor during the various steps of starting, and as the resistance is cut out of the rotor circuit step by step.

These curves may appear a bit complicated at first glance, but study them carefully for a few minutes and you will find them very simple to understand. You will also find that they give a lot of valuable information on the characteristics and performance of slip-ring motors.

197. EFFECT OF SECONDARY RESISTANCE ON STARTING TORQUE

The upper set of curves at A show the starting torque developed by the motor at various percentages of its synchronous speed, and with different amounts of resistance in the rotor circuit.

The heavy irregular line which jumps from curve T-1 to T-2, T-3, and T-4 shows the variations and amount of starting torque as the resistance is cut out and as the motor picks up speed during starting.

To read the value of the torque at any point on any curve, just follow the horizontal chart lines to the left edge of the figure, where the torque can be read approximately, in per cent. of full load torque of the motor. By following the vertical lines downward from any point on a curve, the per cent. of synchronous speed at that point can be found.

For example: The motor is started with full resistance in the rotor circuit, and curve T-1 shows the starting torque commencing at about 185% of full load torque and dropping off to about 160% as the motor reaches 35% speed. Here the first section of resistance is cut out, and the torque is increased to about 295%. Again it gradually reduces as shown by curve T-2, to about 220% when the motor has reached 70% speed.

Cutting out another section of resistance brings the torque back up to about 325% from where it decreases as shown by curve T-3 to about 125% when the motor reaches 92% speed.

Then cutting out the last step of resistance raises the torque once more to slightly over 200%, from which point it drops as shown by curve T-4 to 100% or full load torque as the motor reaches its actual running speed of about 97% synchronous speed.

By cutting out the resistance in this manner, the starting torque is kept high during the entire starting period.

The dotted line at the left end of the heavy line in curve T-2 shows the value of the starting torque

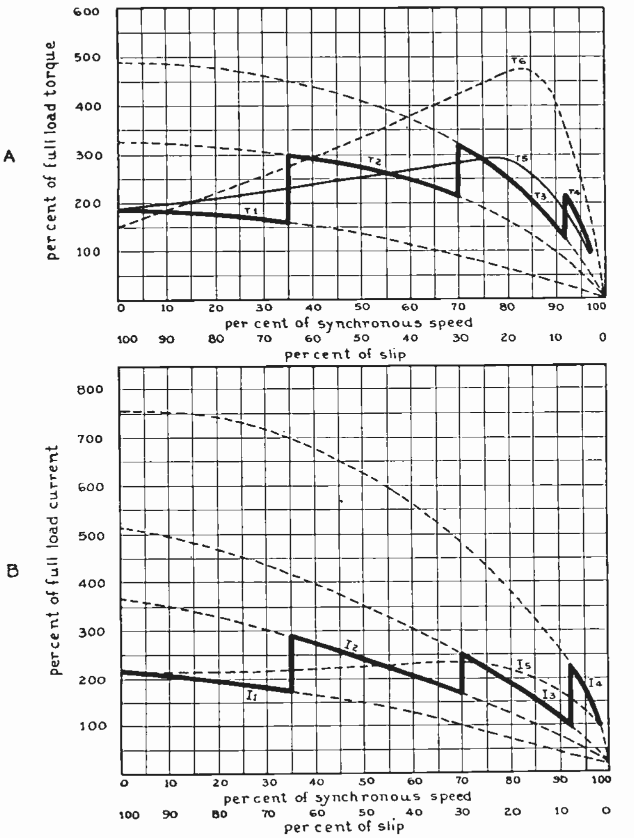

Fig. 185. A shows the torque curves of a slip-ring induction motor as the resistance is cut out of the rotor circuit and the motor comes up to speed. B shows the current curves of the same motor and corresponding to the various steps of the torque curves. Study these curves very carefully with the accompanying explanation.

that would be obtained if the motor were started with one section of resistance already out of the rotor circuit. The dotted line forming the left end of curve T-3 shows the starting torque when starting the motor with two sections of resistance cut out.

The dotted lines forming the right-hand ends of the curves T-1, T-2, and T-3 show how the torque will continue to fall off very rapidly, if the resistance is not cut out as the motor picks up speed.

The light continuous curve T-5 shows the gradual variation in starting torque which would be obtained if the resistance was cut out very smoothly and gradually, instead of in sections or steps.

The continuous dotted curve T-6 shows the starting torque obtained by starting the motor without any resistance and allowing it to come up to full speed in this manner. This curve shows the very important fact that **the torque obtained by starting without any starting resistance in the rotor circuit is at first actually lower than when starting with resistance in the circuit.**

This corresponds with what has previously been mentioned, that **the starting torque of induction motors can be increased by using the proper amount of resistance in the rotor circuit.**

Note also from curve T-6 how the starting torque on constant voltage keeps increasing as the motor speed increases, becoming maximum at about 83% of synchronous speed, and then falling off as the motor approaches closer to synchronous speed.

This is due to the fact that when an induction motor is first started, the difference between the rotor speed and the speed of the revolving magnetic field is very high, and therefore the frequency of the induced rotor currents is high. At this high frequency the rotor currents lag considerably behind the induced voltage, and the torque or power produced is very low.

As the rotor speed increases, the difference between its speed and that of the revolving magnetic field of the stator is less, the frequency of the induced rotor currents is lower, and the power factor is higher; which results in increased torque.

Of course, when the rotor reaches nearly synchronous speed, the lines of force of the rotating magnetic field do not cut across the rotor conductors as rapidly, and the induced voltage and current in the rotor begin to decrease. This causes the torque to reduce somewhat as the motor approaches its rated speed and settles down to operate at its normal percentage of slip, which is always required to produce full load torque.

The percentage of slip is also marked from right to left along the lower side of Figs. 185-A and B. This slip, of course, decreases as the percentage of synchronous speed of the rotor increases.

198. STARTING CURRENT OF SLIP-RING MOTORS

In Fig. 185-B, or the lower set of curves, is shown the current during the various steps of starting a slip-ring motor. You will note that when the motor is started with full resistance in the rotor circuit the starting current as shown by curve I_1 is at first about 215% of normal full load running current. This current reduces gradually as the rotor increases its speed and reduces the slip.

When the motor reaches 35% speed and the first section of resistance is cut out, the current is increased to about 285%, as shown by curve I_2, and so on throughout the following steps of starting the motor.

After the last section of resistance is cut out at about 92% speed, the current decreases as shown by curve I_4, until at about 97% synchronous speed or actual operating speed of the motor, the current has reached 100% or normal full load current.

Note the very heavy starting currents which will be drawn by the motor if it is started without any resistance or with only one or two sections of resistance in the rotor circuit. This is shown by the dotted lines forming the left ends of curves I_4, I_3 and I_2. If this particular motor were started without any resistance the starting current at first would be about 750% or 7½ times full load current, and it would then gradually decrease as the motor speed increases and the slip decreases.

Also note from curved I_5 the more uniform starting current which would be obtained by cutting out the resistance gradually instead of in steps.

The current shown by curve I_5 corresponds to the starting torque shown by curve T_5 in Fig. 185-A.

Each of the other current curves corresponds to the torque curve of the same number in the upper figure.

The efficiency and power factor of slip-ring motors are generally a little lower than those of squirrel-cage motors, but this small loss is frequently more than offset by the other advantages of the slip-ring motors.

When slip-ring motors are used for variable speed service and are being operated below normal speeds their power factor and efficiency will be correspondingly lower than when running at their full rated speed.

The horse power output of motors of this type varies in proportion to the speed at which they are operated. Slip-ring motors generally have approximately the same percentage of slip, or in some cases a little more than that of squirrel-cage motors.

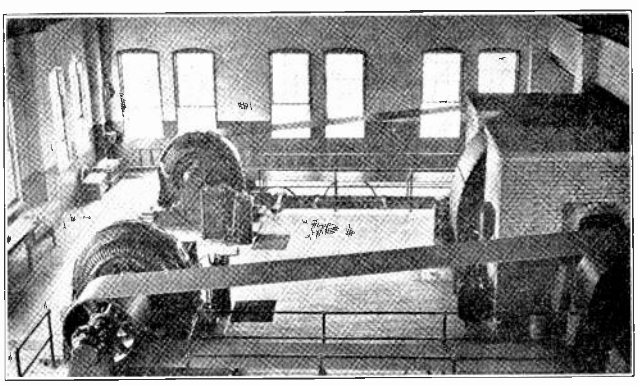

Fig. 186. This photo shows two large slip-ring motors driving a ventilating fan in a mine. The motors are connected to the fan by means of special multiple rope drives.

199. APPLICATIONS OF SLIP-RING MOTORS

Because of their very good starting torque with moderate starting currents and due to the fact that they can be used for variable speed duty, slip-ring induction motors have a large number of applications and types of service to which they are ideally suited.

They are extensively used for driving machines which require frequent starting and stopping, and which are hard to start because of the nature of the load. They are also used for operating devices which require speed variation over a greater range than can be obtained by changing the number of poles of squirrel-cage motors.

Some of the common uses for slip-ring motors are as follows:

- Pump and compressor drives
- Variable speed fans and blowers
- Hoists and cranes
- Rotary dryers and kilns
- Grinders and crushers
- Electric railways
- Electric ship drives.

Fig. 186 shows two 450-h. p. slip-ring induction motors driving a large mine ventilating fan, and Fig. 187 shows a 300-h. p. slip-ring motor which is used to operate a large hoist.

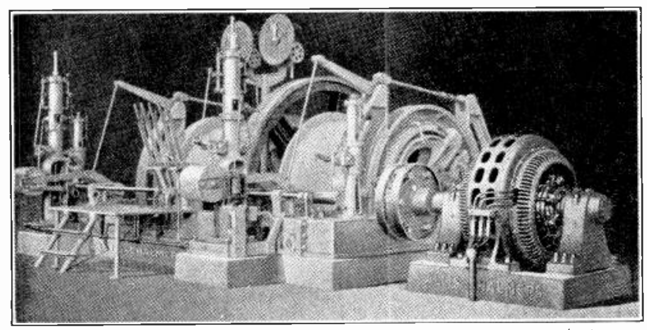

Fig. 187. Large slip-ring motor used to drive the drums of a hoisting machine. Note the manner in which the stator leads are brought up to the motor in conduit which is imbedded in the floor. (Photo courtesy Allis-Chalmers Mfg. Co.)

200. SYNCHRONOUS MOTORS

Synchronous motors operate at synchronous speed, or in exact step, with the applied frequency and the rotating magnetic field of the machine.

When in normal operation, the synchronous motor has no slip, or "zero slip" as it is often called. The speed of these motors is inversely proportional to the number of poles in the stator and directly proportional to the frequency of the applied line voltage, and as long as the number of poles and frequency remain unchanged the speed will not vary.

Therefore, a synchronous motor is a constant-speed motor and can be used where a certain speed must be accurately maintained at all times.

Another great advantage of synchronous motors is that their power factor is very high, and they can actually be operated at leading power factor in order to improve the power factor on a system which is loaded with inductive equipment.

In many cases synchronous motors are used only for power factor correction and are operated without any mechanical load attached. In such cases the motors are connected to the system or lines and allowed to run idle or float on the lines, with their D. C. field poles strongly excited; so that they actually generate and feed leading current into the line and thus help to neutralize the effects of the lagging current produced by induction motors or other inductive equipment on the line.

When these machines are used for power factor correction in this manner they are called synchronous condensers; because their effect on the system is the same as that of a static condenser, which also produces leading current.

Synchronous motors are made for power drives and power-factor-corection in sizes ranging from a few horse power to 50,000 kv-a. or more.

Power companies have synchronous condensers as large as 50,000 kv-a. connected directly to lines of 13,200 volts for correcting the power factor on their systems.

Special synchronous motors are made in very small sizes for the operation of electrical clocks and such devices. Some of these small motors operate on a fraction of one watt of electrical energy.

201. CONSTRUCTION AND EXCITATION

Synchronous motors are constructed almost exactly the same as alternators; in fact, an alternator may in many cases be operated as a synchronous motor. Synchronous motors have the A. C. armature winding or element and a D. C. field the same as alternators.

Small synchronous motors are sometimes made with stationary field poles which are excited by direct current, and with a revolving A. C. armature to which the line current is fed through slip rings.

Most medium and all large-sized synchronous motors, however, are made with revolving fields, the same as large A. C. generators. On these motors the alternating current line-energy is fed to a stationary armature or stator winding which sets up a revolving magnetic field, the same as in induction motors. The field poles on the revolving field or rotor receive their D. C. exciting current through slip rings.

As synchronous motors are always operated from alternating current lines, it is necessary to have some source of direct current for exciting their fields. This field supply is usually obtained from small D. C. exciter-generators, which are either mounted directly on the end of the synchronous motor shaft or may be belt-driven from a pulley on the shaft.

Fig. 188 shows a 75-h. p. synchronous motor of the revolving field type. This motor has its D. C. exciter-generator mounted on the end bracket and driven by the end of the main motor shaft. Note the slip rings and brushes, which are located just inside the end-plate of the synchronous motor and through which direct current from the exciter-generator is passed to the revolving field poles. This motor has six poles and is designed for 60-cycle operation, so its speed will be 1200 R.P.M.

Fig. 189 shows the stator of a large slow-speed synchronous motor, and Fig. 190 shows a large diameter revolving field for a synchronous motor of this type.

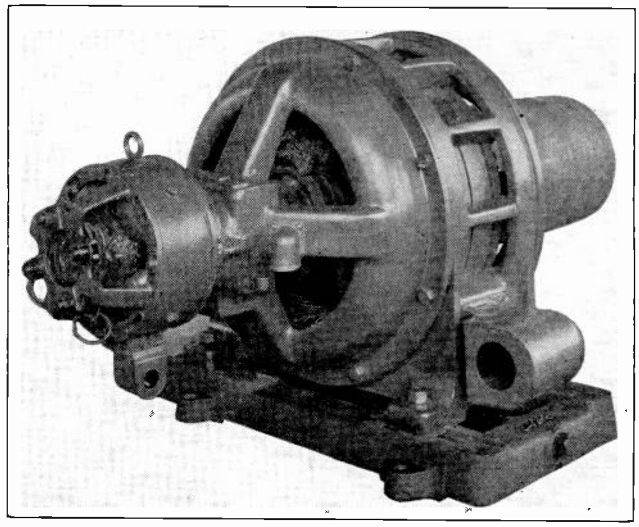

Fig. 188. This photo shows a 75 h. p. synchronous motor of the revolving field type. Note the small exciter-generator which supplies D. C. to the field of the large motor. (Photo courtesy General Electric Co.)

Large synchronous motors with a great number of poles can be made to operate at very low speeds and are, therefore, frequently used to drive slow-speed pumps or machinery by direct connection.

202. DAMPER WINDINGS

In addition to the D. C. windings on the fields of synchronous motors, they are usually provided with a damper winding consisting of short-circuited bars, similarly to the squirrel-cage windings used on induction motors. This damper winding can be clearly seen on the outer ends of the poles of the field rotor in Fig. 190.

Damper windings are provided on synchronous motors to obtain sufficient starting torque to enable the motors to start with some load attached, and also to prevent what is known as hunting. Hunting of synchronous motors will be explained a little later.

203. OPERATING PRINCIPLES

When synchronous motors are started, their D. C. fields are not excited until the rotor has reached practically full synchronous speed; so the starting torque to bring the rotor up to speed must be produced by induction.

When the stator winding of a synchronous motor is excited by being connected to the A. C. line, it immediately sets up the rotating magnetic field with which we are already familiar. The rotating flux of this field cuts across the damper winding of the revolving member or rotor and induces secondary currents in the bars of this winding.

The reaction between the flux of these secondary currents and that of the revolving stator field produces the torque necessary to start the rotor in motion and bring it up to speed.

If no damper winding is provided a synchronous motor will have very poor starting torque, as it must then depend upon the induced currents in the high-resistance field coils and the slight eddy currents in other parts of the rotor. This, however, is sufficient to start some of the older type synchronous motors which were not provided with damper windings, or to start alternators when they are used as synchronous motors.

When some of the older type synchronous motors were used to drive machinery which had to be started under load, they were often started and brought up to speed by means of a separate induction motor just large enough for this purpose.

In other cases, the synchronous motor was attached to the load by means of a friction clutch or magnetic clutch, so that the rotor could be disconnected from the load during starting and then allowed to pick up the load by means of the clutch after the rotor had reached synchronous speed and its D. C. field poles were excited.

This is not necessary with most modern synchronous motors which are properly adapted to their load; because it is possible, by properly proportioning the squirrel-cage damper winding, to design synchronous motors with fair starting torque.

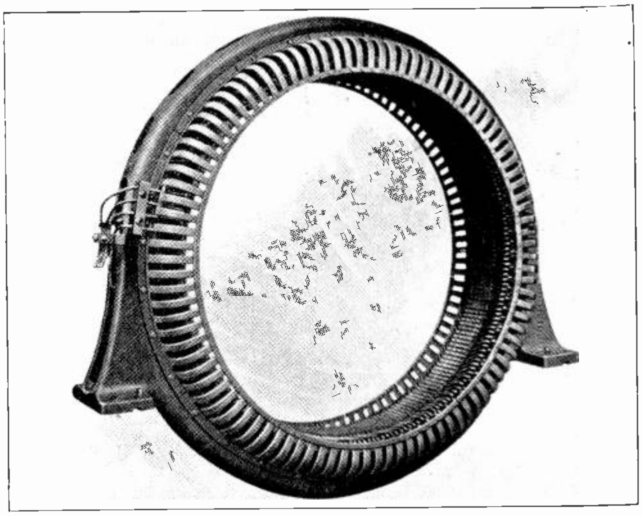

Fig. 189. Above is shown the stator of a large synchronous motor. You will note that the stator, frame, core, and windings are the same as those used for alternators.

When a synchronous motor has been brought up to nearly synchronous speed and is operating as an induction motor because of the damper winding, then the D. C. field poles are excited and the powerful flux of these poles causes them to be drawn into step or full synchronous speed with the poles of the rotating magnetic field of the stator.

During normal operation the rotor continues to revolve at synchronous speed, as though the D. C. poles were locked to the poles of the revolving magnetic field of the stator.

As a synchronous motor has no slip after the rotor is up to full speed, no secondary current is induced in the bars of the damper winding during normal operation.

204. PULL OUT TORQUE

If a synchronous motor is overloaded to the extent where the D. C. rotor poles are made to lag or pull out of step with the poles of the rotating stator field, the slip which results will again cause current to be induced in the damper winding and to develop torque by induction, as during starting.

If the overload is not too great or doesn't last for more than an instant, this torque developed by induction in the damper winding may enable the rotor to pull back into step; but if the overload is too great and lasts too long, the rotor will be pulled out of step with the revolving magnetic field, and the motor will lose its torque and will stall.

If the D. C. current supplied to the revolving field of a synchronous motor is interrupted during operation, the motor will, of course, lose its synchronous torque and will stop if there is a very heavy load connected to it.

We have found that a synchronous motor develops its torque by the attraction between the poles of the revolving magnetic field set up by the stator and the D. C. poles of the rotor, which are maintained at constant polarity by direct current through their coils.

We know that magnetic lines of force are more or less elastic, so we can readily see that it is possible for the D. C. poles of the rotor to be pulled back a little or caused to lag slightly behind the center of the revolving poles of the stator, without actually being pulled out of step far enough to lose the attraction between the poles and thereby lose the torque. This might be caused by sudden surges of load of very short duration.

With a moment's thought we can also see that if a north pole of the revolving field is pulled back and caused to lag a little behind the center of an

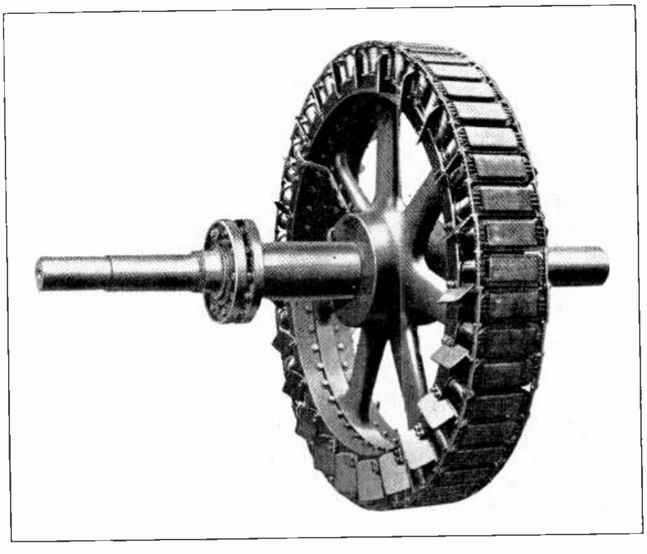

Fig. 190. Revolving field or rotor of a large slow-speed synchronous motor. Note the squirrel-cage damper winding attached to the pole faces and also the slip rings through which the D. C. is passed to the revolving field poles.

unlike pole or south pole of the stator field, this north pole of the rotor will be drawn closer to the adjacent north pole of the stator, which will tend to repel it and add to the torque, thereby keeping the rotor in step if the load is not too great.

205. HUNTING

If a heavy load is suddenly removed from the synchronous motor, the rotor will tend to surge ahead and, due to the elastic nature of the flux, the D. C. poles may for an instant actually surge a little ahead of the revolving poles of the stator.

Sometimes fluctuations in the mechanical load or in the line voltage may in this manner cause the rotor of a synchronous motor to surge or oscillate back and forth more or less irregularly. This is known as **hunting.**

The hunting of the synchronous motor can usually be noticed by a change in the normal operating sound or the smooth, steady hum which is given off by a motor when it is operating properly. The hunting causes a rise and fall, or sort of throbbing note, to come into this sound. This audible note may be of very low frequency, even as low as several oscillations per minute, or it may be of much higher frequency. This will be according to the size and design of the machine and according to the nature of the disturbance which causes the hunting.

Another indication of hunting may be had by watching the pointers of any ammeters connected in the line circuit to the motor. Hunting causes the stator current to increase and decrease, and this will cause the ammeter needle to swing back and forth at the same frequency as that at which the sound or hunting note occurs. During normal operation, the ammeter pointer should change only when the load is changed or when the field excitation is varied.

Hunting may be due to anyone of the following causes: (A) Fluctuations in mechanical load on the motor. (B) Surging of generators on the line. (C) Switching surges. (D) High or low frequency surges. (E) Irregular or pulsating electric loads on the line. (F) Hunting of other synchronous motors on the same line.

Hunting should not be allowed to continue, because it may set up very dangerous mechanical stresses within the motor, and it will also produce objectionable surges of current on the A. C. line supplying the motor.

Damper windings play a large part in the prevention of hunting, because, as soon as the rotor attempts to fall behind or surge ahead of the poles of the rotating stator field, the slip at once causes secondary currents to be induced in the damper winding, and thereby develops inductive torque which tends to hold the rotor at constant speed.

In some cases a synchronous motor may have a tendency to hunt, even though it is equipped with damper windings. Changing the voltage applied to the D. C. field may cause the motor to stop hunting, and if this doesn't stop it, it may be necessary to shut the motor down and restart it. This will often eliminate the hunting.

Sometimes a slight increase or decrease of the mechanical load on the motor may help to stabilize its speed and prevent hunting.

If none of these things will stop it, it will then be necessary to definitely locate and eliminate the cause; which may be in the A. C. supply line, in the exciter-generator, or in the mechanical load.

Fig. 191 shows a large synchronous motor of 2000 h. p., designed for operation on 2300 volts and at unity power factor. Note the exciter-generator, which in this case is mounted on a separate pedestal at the right of the motor. The armature of the exciter is mounted on the motor shaft and is directly driven at the same speed as the synchronous motor.

Fig. 192 shows a three-phase synchronous motor of 150 h. p. which has its exciter driven by means of a large pulley on the end of the motor shaft and a special rope belt. This makes possible the use of a small, high-speed, D. C. generator.

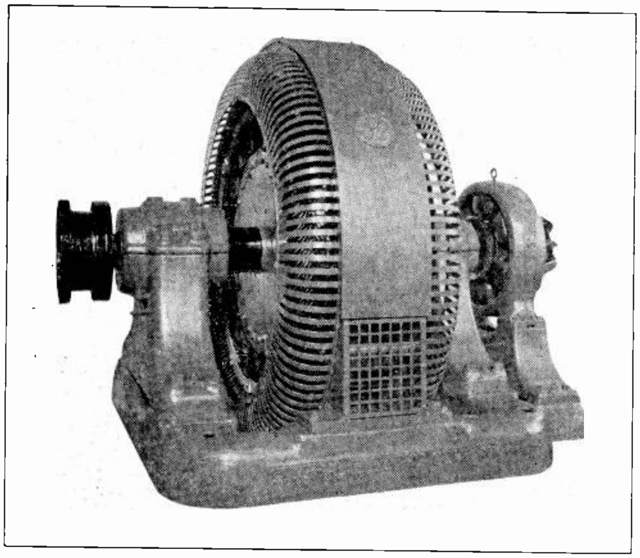

Fig. 191. This photo shows a 2000-h. p., 2300-volt, synchronous motor which operates at 100% power factor. The D. C. exciter-generator is shown on the right-hand end. (Photo courtesy General Elec. Co.)

206. CONNECTIONS OF SYNCHRONOUS MOTORS

Fig. 193 shows a diagram of the connections for a synchronous motor and its exciter-generator. You will note that the wiring and connections for this machine are practically identical with those for an alternator, with the exception that a rheostat is not always used in the field circuit of the synchronous motor.

Regardless of the A. C. voltage at which the synchronous motor may be operated, the exciter voltage is seldom higher than 250 volts. The capacity of the exciter-generator in kw. usually ranges from 1 to 3 per cent of the kv-a. rating of the synchronous motor.

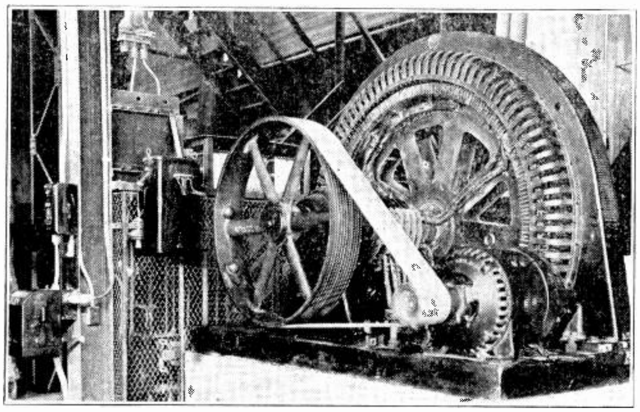

Fig. 192. 150-h. p., 2300-volt, low-speed, synchronous motor and exciter. The speed of the large motor is 144 RPM. (Photo courtesy Allis-Chalmers Mfg. Co.)

By adjusting the exciter field rheostat (F), the voltage applied to the D. C. field of the synchronous motor can be varied. This varies the current flow through the field coils and changes the magnetic strength of the poles. By means of this rheostat the strength of the motor field can be properly adjusted for the mechanical load which it is to drive, and for the amount of power-factor correction it is to perform.

The field discharge switch, D, and resistance, E, are for the same purpose as when used with alternators; that is, to prevent high induced voltages in the field winding when the circuit is interrupted.

The damper winding of the rotor is shown in this diagram by the short-circuited bars in the pole faces.

207. STARTING SYNCHRONOUS MOTORS

When starting the motor, the stator is supplied with alternating current by closing the knife switch or oil switch at "B". Some form of compensator is generally used with large synchronous motors to reduce the voltage applied to the stator when starting, and in this manner keep down the heavy surges of starting current which would otherwise occur.

When starting a synchronous motor, there are a certain number of steps or operations which should be performed in the proper order. This is particularly important when starting large motors. The procedure is as follows:

First, open all switches and see that the field switch is in the discharge position; then apply about 50% of the rated voltage to the stator winding. It may be necessary to apply higher voltage if the motor is to start heavy loads.

As soon as the rotor has reached nearly full speed, see that the exciter rheostat is properly adjusted so that the D. C. generator produces a low voltage as indicated by the voltmeter, V; and with this low voltage excite the field of the synchronous motor very weakly.

Then apply full line voltage to the stator and gradually increase the field excitation until the motor pulls into step, and then adjust the field strength to the proper value to enable the motor to carry the mechanical load, in case it is driving any load of this nature, and for the proper power factor at which the motor is supposed to operate.

Large synchronous motors usually have A. C. ammeters connected in series with the line leads to the stator, and the current input to the motor should not exceed the name-plate current rating, except as per instructions furnished by the manufacturer in regard to the overload capacity of the motor.

Even though a synchronous motor is not driving any mechanical load, it is possibe to overload the stator winding with A. C. by over-exciting the D. C. field and thus causing the motor to draw a large leading current. This, of course, tends to correct the power factor of the system to which the motor is attached, but the synchronous motor should not be overloaded for this purpose any more than it should for driving mechanical load.

208. ADJUSTING POWER FACTOR BY CHANGING FIELD EXCITATION

By adjusting the exciting current, the power factor of a synchronous motor may be varied in small steps from low lagging power factor to a low leading power factor. This makes it possible to vary the power factor of these machines over a wide range and places this characteristic of the motor under the control of the operator at all times.

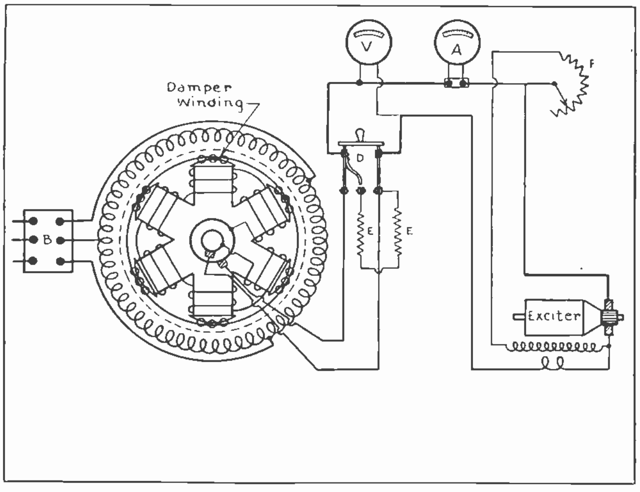

Fig. 193. The above diagram shows the connections for the stator and field of a synchronous motor and also the exciter-generator field discharge switch and instruments.

If a synchronous motor which has normal field excitation were driven as a generator, it would develop the same armature voltage as that which is applied by the A. C. line when the machine is operating as a motor. If the field current is increased above this normal value, the motor will have a leading power factor; and if the field current is below normal value, the motor will have a lagging power factor.

When a synchronous motor is used to drive mechanical load and also to correct power factor, the field will require a small additional amount of exciting current.

209. STARTING COMPENSATORS AND PROTECTIVE DEVICES

Fig. 194 shows a diagram of the connections for a large synchronous motor, including the starting compensator, A. C. ammeter, circuit-breaker, and protective devices.

When starting, the contacts B are opened and contacts C and D are closed, thus supplying reduced voltage to the motor armature J by means of the auto transformer E.

After the motor comes up to speed, the contacts C and D are opened and B is closed, thus supplying the armature or stator winding with full line-voltage.

If at any time during operation the motor is overloaded and the current flow to the stator winding becomes too great, the current in the secondaries of the current transformers H will be increased and will energize the overload trip coils G and G strongly enough so that they will open the circuit-breaker contacts B.

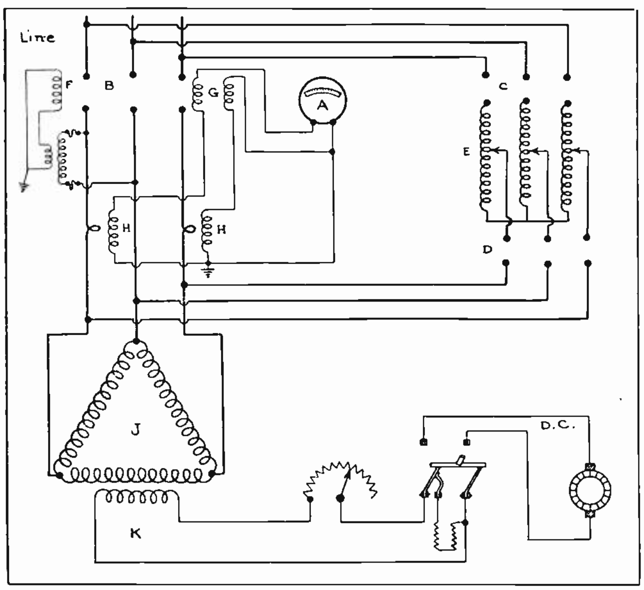

Fig. 194. Diagram of connections for a large synchronous motor with a compensator for starting at reduced voltage. Also note the protective device connected with a circuit-breaker in the line leads.

If the A. C. line-voltage should fail or become too low during operation of the motor, this would also reduce the voltage of the potential transformer secondary and weaken the under-voltage trip-coil F, allowing it to release its armature and open the circuit-breaker B. The D. C. field of the synchronous motor is shown at K.

To stop a synchronous motor or condenser, first decrease the field excitation to normal and then open the line switch. Next open the field-discharge switch and leave it in the discharge position. This switch can be left closed until the machine stops if desired, but should always be opened then.

210. CHARTERISTICS AND ADVANTAGES OF SYNCHRONOUS MOTORS

The efficiency of medium and large-sized synchronous motors ranges from 88% to 96%, depending upon the size, speed, design, etc. Some very large synchronous motors have been built with efficiencies of nearly 98%.

The starting torque of synchronous motors is usually slightly lower than that of induction motors, but many of the later type synchronous motors are designed with starting torques approximately equal to those of squirrel-cage motors.

These starting torques vary from 50% to 150%, according to the design of the machine.

The pull-out torque of synchronous motors varies from 150% to 200% or more of full-load torque.

Several of the outstanding advantages of synchronous motors are: (a) their constant speed; (b) ability to correct power factor, which in turn results in better voltage regulation; (c) higher efficiency at low speeds than induction motors.

The ability of synchronous motors to correct power factor is one of the most important of their advantages.

Synchronous motors have several features which may be considered as disadvantages and these are: (a) they are somewhat more complicated than induction motors; (b) lower starting torque of the older types; (c) tendency to hunt and therefore to fall out of step and stall; (d) they require more skilled attention than induction motors do; (e) they require a supply of both A. C. and D. C.; (f) in case of shorts on the line, synchronous motors act as generators and supply current to the short as long as the inertia keeps the rotor moving at a fair speed. This latter disadvantage can, however, be eliminated with proper protective relays.

211. APPLICATIONS OF SYNCHRONOUS MOTORS

The advantages of synchronous motors for certain classes of service much more than make up for the disadvantages which have just been mentioned.

Fig. 195 shows two 2600 h. p. synchronous motors used to drive low-pressure water pumps of the screw-propeller type. Fig. 196 shows a group of synchronous motors driving compressors in an ice plant.

Synchronous motors have a very wide field of application and their use is being rapidly extended to other classes of power drives each year. A large number of power generating and public utility companies insist that all motors of 50-h. p. and larger which are connected to the lines must be of the synchronous type. This is done in order to improve the power factor of the system and thereby permit better utilization of the generator line and transformer capacities.

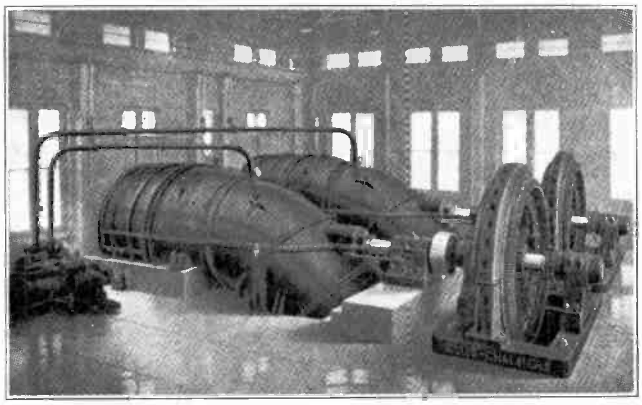

Fig. 195. This photo shows 2600-h. p. synchronous motors driving low-pressure, screw type water pumps. (Photo courtesy Allis-Chalmers Mfg. Co.

With lower power factors, a large portion of the generator, line and transformer capacities must be used for the circulation of lagging wattless currents.

A number of the more common uses or applications for synchronous motors are as follows:

Operation of compressors and pumps; operation of fans and blowers, motor-generators, and frequency changers; steel mill drives; paper mill drives; crushers and grinders; line-shaft drives; and as synchronous condensors for power-factor correction only.

212. SUPER-SYNCHRONOUS MOTORS

It has previously been mentioned that, in order to start with loads, synchronous motors are sometimes connected to the load by means of friction or magnetic clutches. A variation of this principle is used on a special synchronous motor which has been designed for starting heavy loads and is known as a super-synchronous motor.

This type of motor has the stator frame arranged so that during starting the entire frame and core can revolve on auxiliary bearings on the motor shaft. This allows the rotor, which is attached to the load, to remain stationary until the stator is revolving around it at full synchronous speed.

The field is then excited with D. C. and a brake is gradually applied to the stator frame, causing it to reduce speed and finally bringing it to a complete stop. This gradually exerts upon the rotor poles the full running torque of the synchronous motor, and as soon as the brake is applied the rotor begins to turn and drive the load, coming up to full synchronous speed by the time the stator frame is completely stopped.

This method permits the use of the full running torque to start the load and allows the starting to be accomplished at much higher power factor.

Fig. 197 shows a 300-h. p. super-synchronous motor of the type just described. In this figure you will note that the stator frame is not attached to the bearing pedestals but is instead mounted on its own bearings on the motor shaft. You will also note

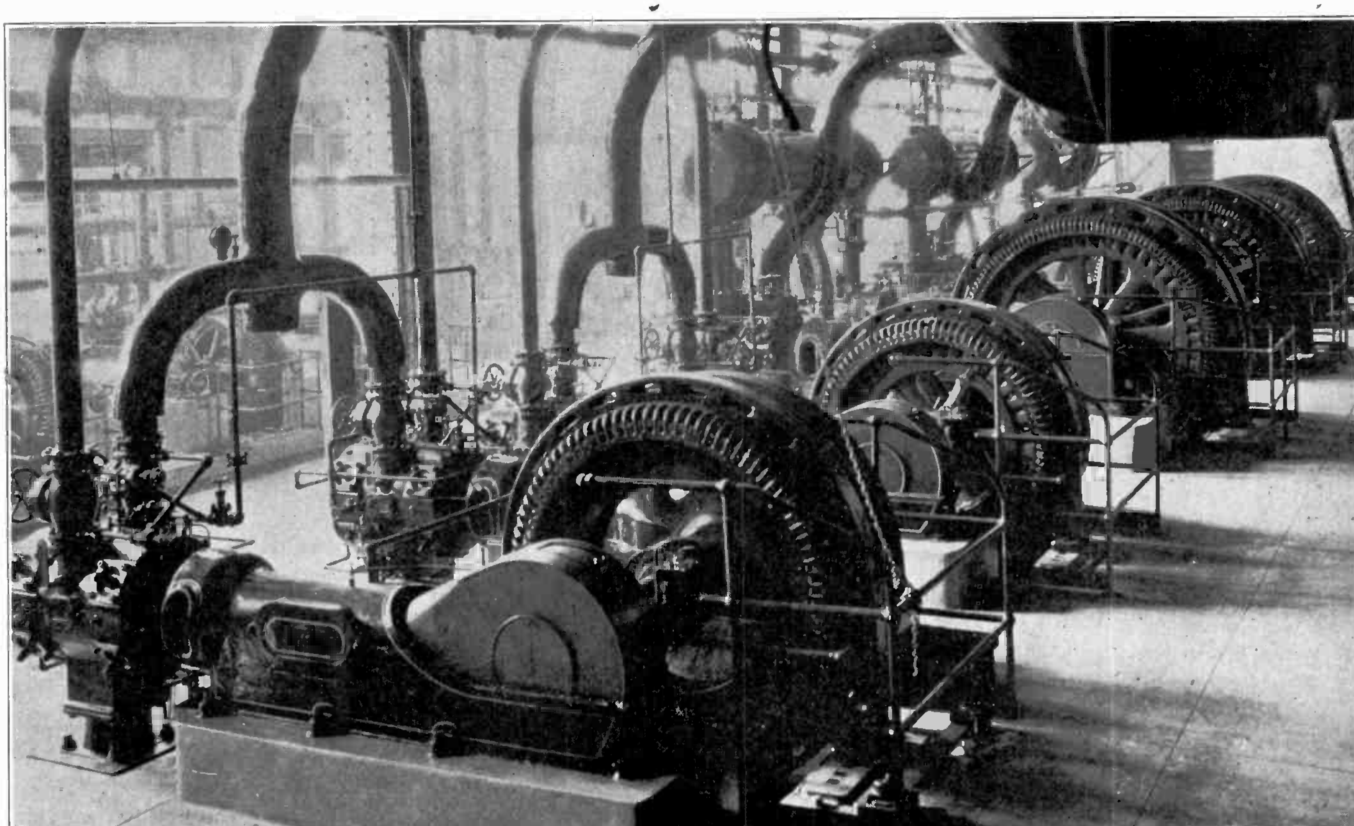

Fig. 196. Group of large synchronous motors used to drive compressors in an ice plant. Many large ice plants and refrigerating plants use motors of this type to operate their ice machines.

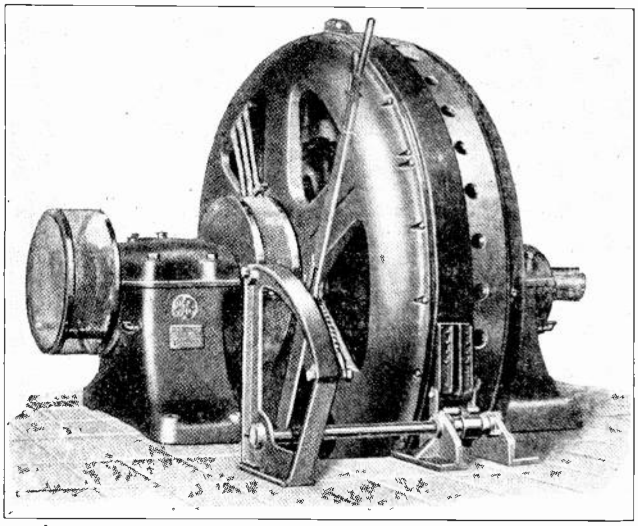

Fig. 197. Super-synchronous motor which is equiped with a revolvable stator and brake to obtain high starting torque. (Photo courtesy G. E. Company.)

the brake-band around the outside of the stator frame and the brake-link and lever which are used to tighten the band and stop the rotation of the stator and thereby cause the rotor to start the load.

The slip rings of this motor are mounted on the left end of the shaft inside of the protective screen, and the leads are taken through the hollow shaft to the D. C. rotor poles.

Fig. 198 shows a group of large super-synchronous motors in use in a cement mill. Two sets of slip rings must be used with motors of this type; one set for conveying the alternating current energy to the stator or armature when it is revolving during starting period, and the other set for supplying the direct current to the rotor, which revolves all the time during the operation.

The method of calculating the proper size of synchronous condenser to use for correcting the power factor of a system, will be covered in later paragraphs.

213. SPECIAL A. C. MOTORS

In addition to the common types of A. C. motors which have just been explained and which are in very general use throughout the entire electrical industry, there are also a number of special A. C. motors which are designed with certain characteristics to meet unusual requirements.

Several types of these which have been more recently developed are proving very satisfactory and have excellent advantages for certain classes of work. Some of these motors, or the principles involved in their design, will come into much more extensive use in the next few years, and for this reason they are worth a little special attention at this point.

The principles on which these motors operate are in general more or less similar to those of common types of machines with which you are already familiar. Therefore, it is not necessary to go into great detail in discussing them; so we shall merely explain the application of these principles to several of the most popular types of special motors and shall also explain the characteristics and applications of these machines.

214. DOUBLE SQUIRREL-CAGE MOTORS

We have already learned that it is possible to obtain much better starting torque from induction motors by the use of a certain amount of resistance in the rotor circuit. It is not always desirable to use a slip-ring motor with the auxiliary controls required; and, if squirrel-cage motors are designed with rotors of very high resistance, this resistance while improving their starting torque, will also decrease their running efficiency.

To obtain the very good starting torque of the high-resistance rotor and also the higher running efficiency of the low-resistance rotor, induction motors have been developed with what are called **double squirrel-cage rotors.**

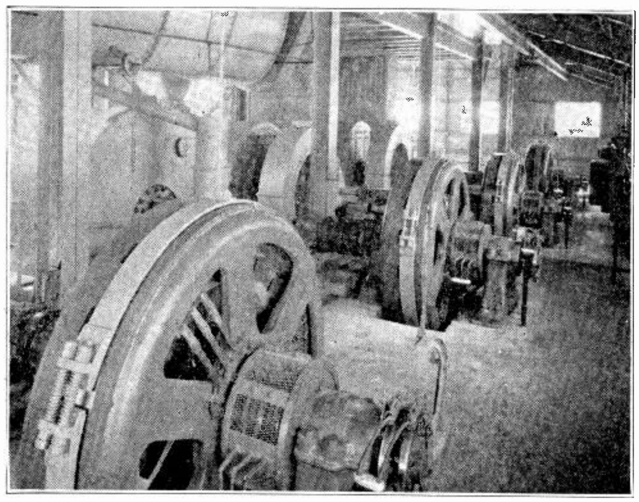

Fig. 198. This photo shows four large low-speed super-synchronous motors operating at 2200 volts and driving machines in a cement mill. (Photo courtesy G. E. Company.)

These rotors consist of the usual core of laminated iron equipped with specially-shaped slots in which are imbedded the bars of two squirrel-cage windings. One squirrel-cage with large bars of low resistance is imbedded deeply in the iron core in the bottoms of the slots, and another squirrel-cage with smaller bars of higher resistance is located close to the outer surface of the rotor core with the bars placed just beneath the core surface.

Fig. 199 shows on the left a sectional view of such a rotor which has been cut in two to show the position of the high-resistance squirrel-cage at "A" and the low-resistance squirrel-cage at "B". On the right in this figure is another view of a double squirrel-cage of this type from which the iron core has been removed by acid. This view shows very clearly the construction of the inner or low-resistance element and the outer or high-resistance element

Fig. 200 shows a complete rotor of the double squirrel-cage type in which the bars and end rings of the squirrel-cages are cast of aluminum which has been poured directly into the openings in the iron core, thus making it one very solid unit when completed.

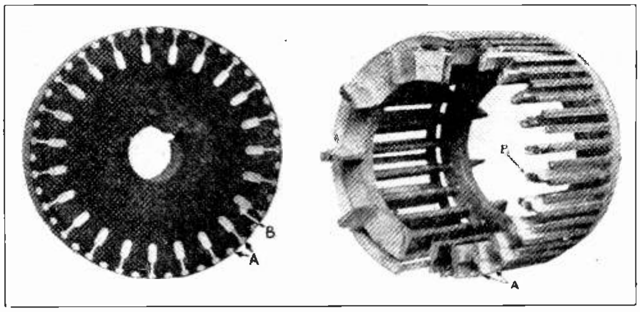

Fig. 199. This figure shows two views of a double squirrel-cage rotor. On the left is a sectional view and on the right the core iron has been eaten out by acid, clearly showing the construction and shape of the double squirrel-cage. (Photo courtesy General Electric Co.)

215. OPERATING PRINCIPLES

These motors have an ordinary stator winding, the same as any polyphase induction motor. When the stator is supplied with A. C. from the line, the revolving magnetic field induces secondary currents in both of the squirrel-cage windings and sets up the torque which starts the motor.

During starting, however, the outer or high-resistance squirrel-cage is the one which is most active, and very little current is carried by the inner cage during this period. This is due to the fact that the smaller high-resistance bars are located near the outer edge of the rotor core and have much less iron or magnetic material around them. This means that they provide a path of much lower reactance than the inner bars, which are completely surrounded with a heavy path of iron.

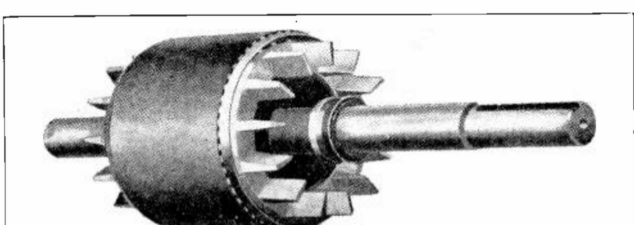

Fig. 200. Complete rotor of the double squirrel-cage type. Note that there are no open slots around the rotor core, the bars being cast into the rotor.

This outer winding of low reactance provides a much easier path for the high-frequency secondary currents which are induced during starting when the slip of the motor is very great. After the motor is up to nearly full speed and the slip is very small, the frequency of the induced rotor currents is then much lower, and as low frequency A. C. can pass through an inductive circuit much easier than high frequency, the low-resistance bars of the inner squirrel-cage now offer an easy path for the flow of rotor current during normal running of the motor.

We find, therefore, that the changeover of the current from the high-resistance, starting squirrel-cage to the low-resistance, running cage is entirely automatic and requires no switches or moving contacts; being due entirely to the change of frequency and magnetic characteristics of the rotor between the period of high slip during starting and reduced slip when running.

Double squirrel-cage motors are very suitable for jobs which require heavy starting torque and where simple, rugged motors requiring a minimum of maintenance are desired. The double-squirrel-cage principle is not altogether new, having been used in induction motors since their early development; but it is only in recent years that this principle has come into general use in commercial power motors.

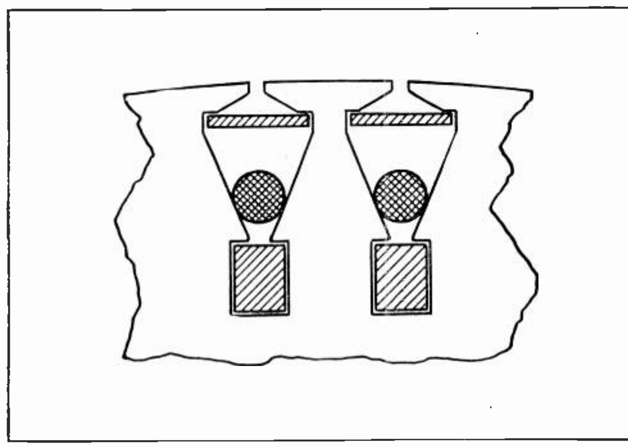

Fig. 201. This sketch shows the slot and bar construction of double squirrel-cage rotors using iron "choker bars" to change the resistance of the field and outer circuits.

216. DOUBLE-SQUIRREL-CAGE MOTORS WITH "CHOKER BARS"

Several different styles of double-squirrel-cage motors are in use at present. Some of these use different variations of the principle, but in general their operation is very much the same. One motor of this type which is made by the Fairbanks Morse Company, uses a set of loose iron bars or rods which are placed in the slots between the inner and outer squirrel-cage bars. These bars change their position by centrifugal action when the motor comes up to speed, thus changing the magnetic path and thereby varying the reactance of the squirrel-cage circuits.

Fig. 201 shows a cross-sectional view of two slots of a rotor of this type. The low-resistance squirrel-cage bars are located in the inner slots, and the high-resistance squirrel-cage bars are the thin flat ones shown near the outer edges of the slots.

When the motor is first started, the round iron bars are held in the bottom of the slots by the magnetic action of the flux set up in the rotor. This completely closes the iron path around the inner squirrel-cage, making this path one of very high impedance, so that only a very small amount of the starting current flows in this winding.

When the motor reaches nearly full speed, the iron bars are thrown outward by centrifugal force, thereby decreasing the amount of magnetic material around the inner bars, and increasing the amount of iron around the outer bars.

This reduces the reactance of the inner squirrel-cage and increases the reactance of the outer one which, we recall, is already of high resistance. This causes a very decided shift of the lower frequency currents induced in the rotor during running, from the high-resistance rotor to the one of low resistance.

217. BTA VARIABLE-SPEED A. C. MOTORS

Another type of A. C. motor, known as the BTA motor, has been developed by the General Electric Company to meet the needs of various power-driven machines which require adjustable speed A. C. motors with characteristics similar to those of the shunt D. C. motor.

These motors have a stator winding and two windings on the rotor, and also use a commutator and brushes similar to those of a D. C. machine.

Fig. 202 shows a diagram of the windings and connections of a motor of this type. You will note that the alternating current line connects to one of the rotor windings, "P", by means of the brushes and slip rings. When this winding is excited with A. C. from the line, it sets up a revolving magnetic field and also induces secondary currents in the stator windings: S-1, S-2, and S-3.

The winding in the stator is constructed similarly

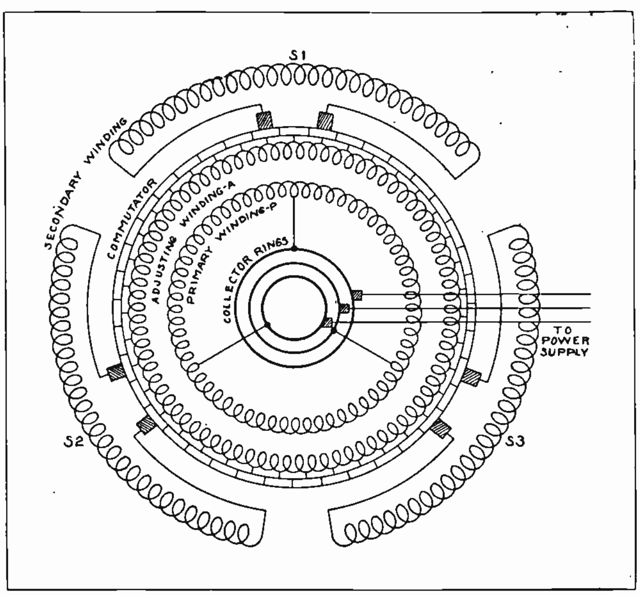

Fig. 202. This diagram shows the connections of the armature and stator windings of a BTA variable speed A.C. motor. Examine the diagram carefully while reading the accompanying explanation.

to stator windings of ordinary induction motors, except that the three phases are connected separately to the three pairs of brushes which rest on the commutator. These brushes are adjustable and can be moved closer together or farther apart. When they are resting on the same commutator segment the stator windings are short-circuited, so that a rather heavy flow of induced secondary current is set up in these windings.

The adjusting winding, "A", which is also carried on the revolving armature and is connected to the bars of the commutator, generates a certain amount of voltage which is applied to the brushes that connect to the stator winding.

When these brushes are moved farther apart, a greater amount of adjusting voltage is applied to the stator windings. By shifting the brushes and varying this voltage, the speed of the motor can be changed.

218. CHARACTERISTICS

These motors are usually built for a range of speed variation of three to one, and are designed to operate at constant torque at any speed within their range. This means that the horse power will be proportional to the speed at which they are operated.

The efficiency of these motors remains nearly constant over the greater part of their speed range, but is slightly lower at the lowest operating speeds. Their average efficiency is high compared with that of wound-rotor induction motors having secondary resistance.

The power factor of this type motor is about the same at synchronous speed as the power factor of an ordinary induction motor of the same size, and becomes higher when the motor is operated at higher speeds.

BTA motors will develop from 140 to 250 per cent. of full-load torque during starting and with starting currents of only 125 to 175 per cent. This ability to develop heavy starting torques with comparatively small starting current is one of the very desirable features of these motors.

When operating at their lower speeds, the pull-out torque of these motors is from 140 to 250 per cent. of full-load torque, and when operating at higher speeds the pull-out torque varies from 300 to 400 per cent. of normal-load torque.

Fig. 203 shows the armature of a BTA motor removed from the machine. The commutator is connected to the adjusting winding on the armature similarly to the connections for an ordinary D. C. motor armature and commutator. The slip rings on the left end of the shaft have leads taken from them through the hollow shaft to the A. C. winding on the armature.

You will note also the ventilating fan which is attached to the armature at the rear of the commutator.

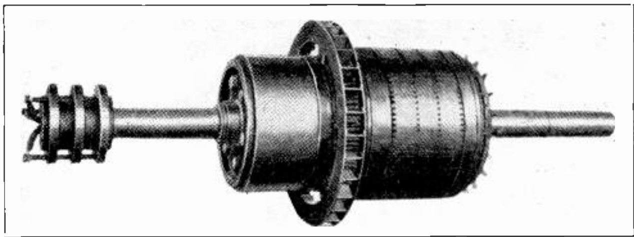

Fig. 203. Armature of a BTA motor showing the commutator, slip rings, and ventilating fan. (Courtesy G. E. Company)

Fig. 204 shows a complete BTA motor. The small hand-wheel on the upper arm of the end-bracket is used for adjusting the position of the brushes and thereby changing the motor speed. The collector rings on the end of the shaft are enclosed in a safety hood or guard, as shown. The line leads are brought out of this hood for connection to the three-phase A. C. line.

The small box on the side of the motor frame near the base contains an overload relay to protect the motor from too heavy overloads. This relay is connected to the starting switch or motor controller so that it will trip the starter and open the line circuit in case of excessive overload currents to the motor.

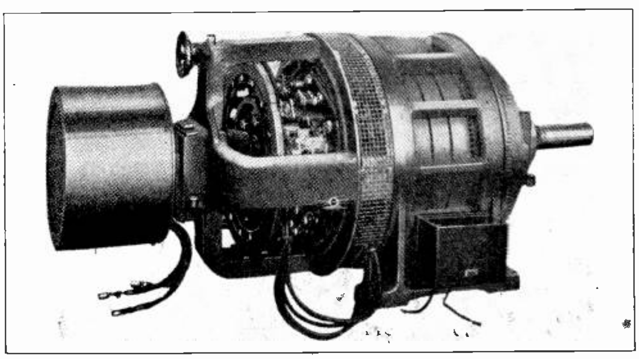

Fig. 204. This photo shows the completely assembled BTA motor. The brush-shifting wheel can be seen on the upper corner of the frame and the slip rings are enclosed in the housing at the left end of the shaft. (Courtesy G. E. Company)

Fig. 205 shows the standard ratings of type BTA motors. These are made in six, eight, and ten-pole types for normal speeds of 1200, 900, and 720 R.P.M. You will note from the table that the six-pole machines can be varied above or below their normal speed of 1200 R.P.M., within a range of 550 to 1650 R.P.M. The normal speed of 900 R.P.M. for the eight-pole machines can be varied from 415 to 1215 R.P.M., and the normal speed of 720 for ten-pole machines can be varied from 333 to 1000 R.P.M.

You will also note from the center column of the table that the horse power varies in proportion to the speed. For instance, the 5-h. p. motor develops only 1.67 h. p. at its lowest speed of 550 R.P.M. In other words, when the speed is reduced to one-third the horse power is also reduced to one-third.

The motor with maximum rating of 10-h. p. at high speed develops only 3⅓ h. p. at its lowest speed, etc.

219. FYNN-WEICHSEL MOTORS

Another special type of motor which is manufactured by the Wagner Electric Corporation, is known as the **Fynn-Weichsel** motor. These motors are really combination induction and synchronous motors, and have excellent starting torque and very high power factor when running fully loaded. They start as an induction motor and will start loads of 150% or more of full load, quickly bringing them up to full speed, and at this point the motor changes over and runs as a synchronous motor during normal operation.

If during operation the motor is overloaded beyond 160% of full load current, it will pull out of synchronism and again operate as an induction motor up to overloads of approximately 250% or more before it will stall.

These characteristics have made this type of motor very popular in the last few years for certain classes of drives where motors with good starting torque, constant speed, and high power-factor are required.

Another decided advantage of the Fynn-Weichsel motor is that it supplies its own direct current for exciting the D. C. field winding, and therefore does not require separate exciter-generators as ordinary synchronous motors do.

220. CONNECTIONS AND OPERATING PRINCIPLES

Fig. 206 shows a diagram of the windings and connections for a Fynn-Weichsel motor. The revolving armature or rotor has a main A. C. winding connected to slip rings and to the A. C. line. In addition, it also has a small D. C. winding which is connected to the commutator and develops in the neighborhood of 24 volts of direct current for excitation of the D. C. field poles.

This field winding is placed in the slots of a stator and is uniformly distributed over the stator core, instead of being wound on projecting field poles as in the ordinary synchronous motor.

The diagram in Fig. 206 shows the D. C. field-winding connected to the brushes of the commuta-

Rating of Standard BTA Motors

Number of Poles	H.P.	Full Load Speed
6	5/1.67	1650/550
6	7.5/2.5	1650/550
6	10/3.33	1650/550
6	17.5/5.83	1650/550
8	25/8.33	1250/415
8	35/11.67	1200/415
10	50/16.67	1000/333

Fig. 205. The above table gives the horsepower rating and speed ranges of standard BTA motors. Note how the h.p. varies with the speed.

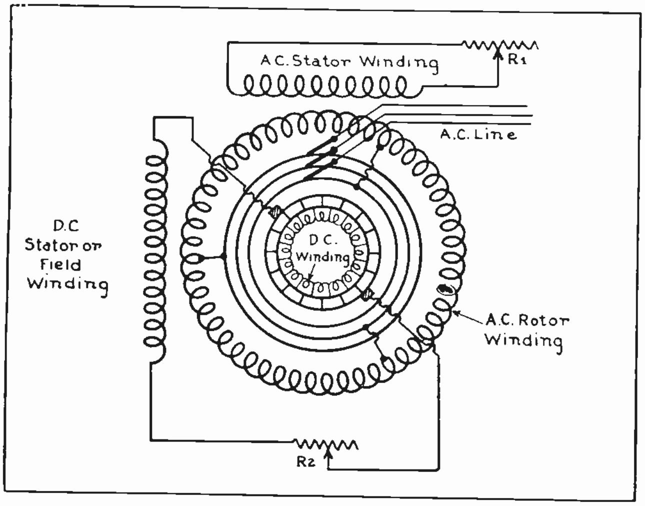

Fig. 206. Diagram showing the connections of the armature and field of a Fynn-Weichsel motor. Note that both the stator and armature have two separate windings.

tor and equipped with a rheostat for varying the field strength. In this simple diagram the single coil or winding shown is used to represent the entire field winding and whatever number of poles it may actually contain.

There is also an A. C. winding which is placed in the slots of the stator and is connected through a rheostat to form a closed circuit upon itself. This winding is located 90 degrees from the D. C. winding in the stator.

When alternating current is applied to the slip rings and the A. C. winding on the rotor, it sets up a revolving magnetic field and also induces secondary currents in both the A. C. stator-winding and the field winding.

The reaction between the flux set up around these windings and the field of the A. C. rotor winding, develops excellent starting torque and quickly brings the motor up to full speed. As the speed of the motor increases to synchronism, D. C. voltage is obtained from the commutator and small winding and applied to the brushes. This D. C. voltage is applied to the field and increases the strength of the D. C. field winding and causes the motor to hold in synchronism and operate as a synchronous motor during normal running conditions.

If the motor is overloaded beyond the pull-out torque capacity of about 160% full-load torque, it will then fall out of step and operate as an induction motor, once more continuing to carry the overload at slightly reduced speed.

During starting of the motor, rheostat R-1 is adjusted to include the proper amount of resistance in series with the A. C. secondary winding in the stator. This resistance is cut out as the motor comes up to speed and the winding is then short-circuited.

When the motor pulls into synchronous speed there is no more slip, so there will be no appreciable current induced in this stator winding as long as the motor operates as a synchronous machine.

If the motor is overloaded to a point where it pulls out of synchronous operation and slightly reduces its speed, this recurrence of the slip will immediately cause current to be induced in the stator winding once more and thus develop by induction the added torque which enables the motor to carry the very heavy overloads which it is capable of carrying as an induction motor.

221. LEADING POWER FACTOR AND P. F. ADJUSTMENT

Rheostat R-2 can be adjusted to obtain the proper strength of the D. C. field-winding according to the load the motor is required to carry and the power factor which it is desired to maintain.

At full load the Fynn-Weichsel motor generally has a power factor of about 92% leading. From this we can see that if one or more motors of this type are used in a plant with induction motors and other inductive equipment they will improve the power factor considerably.

In fact, a 15-h. p. Fynn-Weichsel motor with its leading power factor will just about neutralize the lagging power factor of the 15-h. p. slip-ring, induction motor, thereby keeping the power factor at approximately unity on the line or system on which the two motors are operated in parallel.

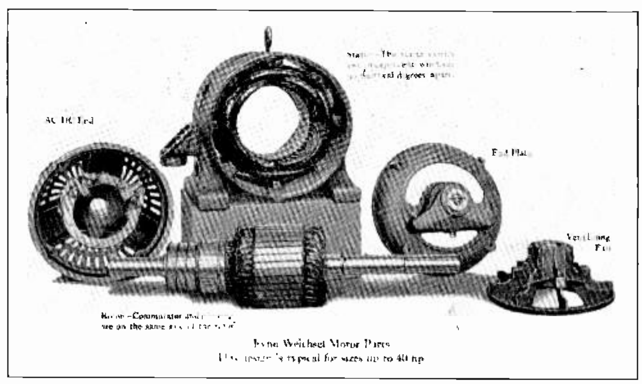

Fig. 207. Disassembled view of Fynn-Weichsel synchronous motor. Note the commutator and slip rings both on the same end of the shaft and also the two windings in the stator. (Photo courtesy Wagner Electric Corp.)

While the power factor of squirrel-cage induction motors becomes very low when they are operating lightly loaded, the power factor of the Fynn-Weichsel motor remains practically constant with any decrease of load which ordinarily occurs on a motor properly selected for its drive.

Fig. 207 is a disassembled view of a Fynn-Weichsel motor and shows clearly the construction of the rotor with its commutator and slip rings, and also the arrangement of the D. C. and A. C. windings in the stator.

Fig. 208 shows a complete Fynn-Weichsel motor with protective guards over the commutator, slip rings, and **brushes.**

222. SPECIAL ENCLOSED-TYPE MOTORS

In certain plants and classes of work where motors must operate in an atmosphere that is filled with dust or vapors it is often very difficult to keep the ventilating spaces in the motor windings from clogging with dust or to prevent the insulation of the windings from being damaged by vapors.

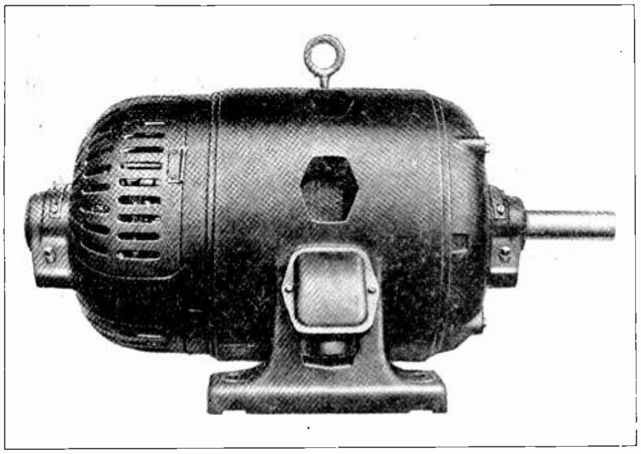

Fig. 208. This photo shows a completely assembled Fynn-Weichsel motor with a guard enclosing the slip rings and commutator. (Courtesy Wagner Electric Corp.)

To meet these conditions there are motors now being built with the winding, rotor, and bearings completely enclosed in an air-tight casing. These motors are so designed that the heat from the windings is conducted to the outside through the metal shell or casing. The regular motor casing is in turn enclosed in an outer jacket which guides a strong draft of cooling air directly over the surface of the motor casing, thus greatly aiding in the cooling of the machine.

Fig. 209 shows several views of a motor of this type. The upper left view shows the end from which the cooling air is exhausted from the jacket. The upper right view shows the air-intake end, with a screen which prevents coarse objects from getting into the fan and also protects an operator's hands from coming in contact with the revolving fan-blades. The lower view shows the motor and its enclosing frame removed from the air jacket and also shows the large ventilating fan used to form the strong draft of air over the motor casing. Motors of this type can be operated in extremely dusty places without injury to field windings or bearings by dust or vapors in the air, and also without the explosion hazard which accompanies the use of open commutator or slip ring types.

There are a number of other special types of motors which have been developed to fit almost every requirement and class of service for which a power drive is required. However, the general principles of these machines are very much alike and are similar to those which have been described in this section; so you will have no trouble in understanding almost any type which you may encounter.

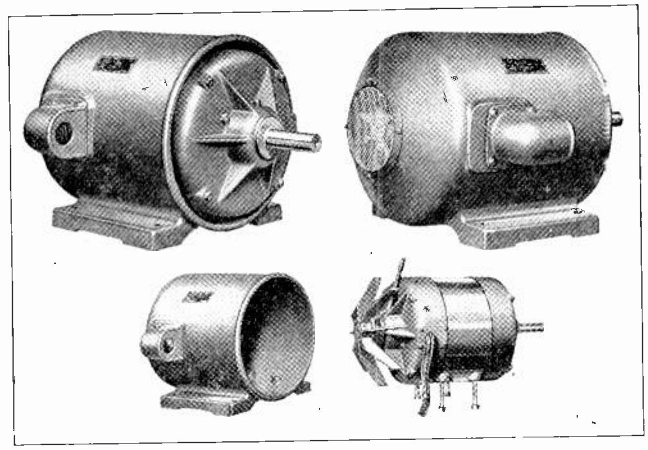

Fig. 209. Completely enclosed A.C. induction motor with special air-jacket to direct the cooling air over the surface of the motor casing. These motors are ideal for use in extremely dirty locations or in places where there are explosive vapors or dust.

223. PORTABLE MOTORS FOR FARM USE

Fig. 210 shows a polyphase induction motor and push-button starter mounted on a convenient portable truck, with a heavily insulated extension cord for connecting the motor to a nearby line or transformer. Portable motors of this type are very convenient for certain temporary drives in industrial plants and factories, and are also coming into quite extensive use on farms.

There are numerous profitable uses for electric power on the farm, and many thousands of farms are well electrified and making excellent use of electricity for both light and power purposes.

Fig. 211 shows a portable electric motor being used for driving a hay baler. Motors of this type can also be used to operate threshing machines, pumps for irrigation and stock watering purposes, ensilage cutters, feed grinders, line-shafts in machine repair shops, and many other uses.

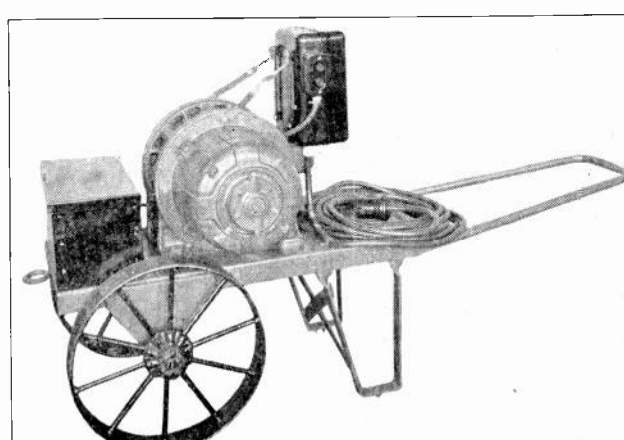

Fig. 210. Portable A.C. induction motor particularly adapted for use on farms and for driving portable machinery. (Courtesy G. E. Company.)

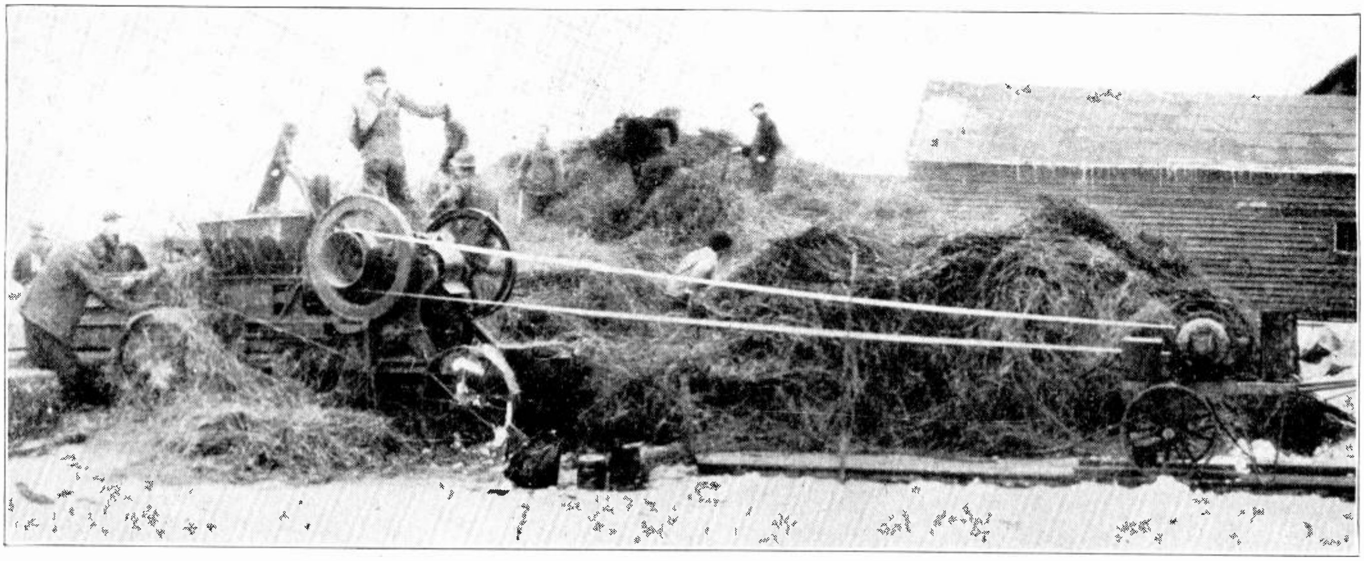

Fig. 211. This photo shows a portable A.C. motor driving a hay baler. Many thousands of farms are making excellent use of electricity to save time and money in many ways, and taking advantage of the increased safety obtained by use of electrical power equipment. (Photo courtesy G. E. Company)

224. ELECTRIC MOTORS FOR USE ON SHIPS

Electric motors are also used extensively in ships of all classes. Battle ships are using enormous electric motors for driving their propellers, and also numerous small motors for handling equipment aboard the ship. Merchant marine ships use numerous electrical motors for operating cranes, derricks, hoists, elevators, and conveyers in handling materials when loading and unloading the ship.

Many of the smaller and medium sized motors for deck use on ships are enclosed in special air and water-tight casings, to exclude all salt water and vapor.

Electrical dredges use powerful electric motors to operate soil and rock cutting tools as well as the enormous suction pumps with which these dredges are equipped.

Modern passenger liners may have as many as several hundred medium and large sized electrical motors, in addition to the numerous small ones which are used for fans and convenience devices.

Two of the large ships in the U. S. navy are each equipped with eight motors of 22,500 h. p. each, which are used for propeller drives.

So we find electric motors are the principal source of mechanical power in practically all classes of industry and even on the farms and ocean-going ships.

POWER-FACTOR CORRECTION

Throughout the first section on A. C. and in a number of places in this section on A. C. motors, we have mentioned the desirability of maintaining good power factor on alternating-current systems.

We have also found that induction motors operate at lagging power factor even when fully loaded, and that they are particularly detrimental to the power factor when they are allowed to operate lightly loaded.

Some of the disadvantages of low power factor are as follows: It causes wattless currents to flow through the feeder lines and alternator windings, thereby requiring larger alternators, transformers, lines, switches and fuses, or causing overheating of those already in use. Low power factor causes increased voltage drop and poor voltage regulation on the lines and systems in which it exists. This voltage drop may result in low voltage at the terminals of motors and other equipment and cause them to develop very poor starting torque.

So we find that low power factor makes necessary the use of expensive voltage-regulating equipment, larger alternators and transformers, larger conductors in the lines and feeder circuits, and increased size of motors to perform a given amount of mechanical work.

In addition to these things, low power factor is often the cause of increased power bills because some power companies have in their power contracts a penalty clause on low power factor.

We have learned that lagging power factor can be neutralized and the power factor of a system improved by the use of synchronous motors or static condensers, which operate at leading power factors and supply leading currents which neutralize the lagging currents of inductive equipment.

225. USE OF SYNCHRONOUS MOTORS AS CONDENSERS

Synchronous motors operating with over-excited fields and used as **synchronous condensers** are very frequently installed for correcting the power factor in industrial plants and on the lines of power companies.

Synchronous condensers are generally used for power-factor correction where more than 500 kv-a. of corrective energy is to be handled, and they are also commonly used in sizes down to 50 kv-a.

In industrial plants where a large number of A. C. induction motors are in use, it is often advisable and economical to replace some of these with synchronous motors to drive certain machinery or equipment which is suited to the characteristics of synchronous motors.

In this manner the synchronous motors can be used to furnish mechanical power and also to correct power factor. In other cases, medium or large sized synchronous motors are connected to the lines or system wiring without any mechanical load and allowed to float on the system just for power-factor corrective purposes. They are then known as **synchronous condensers.**

Sometimes an idle A. C. generator can be used in this manner and allowed to run idle on the A. C. lines with its field strongly excited. This improves the power factor on the system and will often greatly reduce the amount of wattless current flowing in the lines and required from the other alternators which feed the system.

Synchronous condensers of large capacity have the advantage of being of lower first cost than static condensers of equal capacity, and also of being much smaller in size for a given kv-a. capacity on the larger units. They also possess the advantage of affording easy adjustment of the power factor by regulation of their field excitation, and their operating characteristics tend to maintain good voltage regulation on the circuits to which they are attached.

The disadvantages of synchronous condensers are that they have somewhat higher losses and require more care and maintenance than static condensers. Synchronous condensers are commonly installed where the power factor of a large system can be corrected from one central point.

Fig. 212 shows a synchronous condenser of 5000 kv-a. capacity, for 2300-volt operation. This machine is enclosed in an air-tight casing and is cooled by clean, dry, ventilating air which is forced

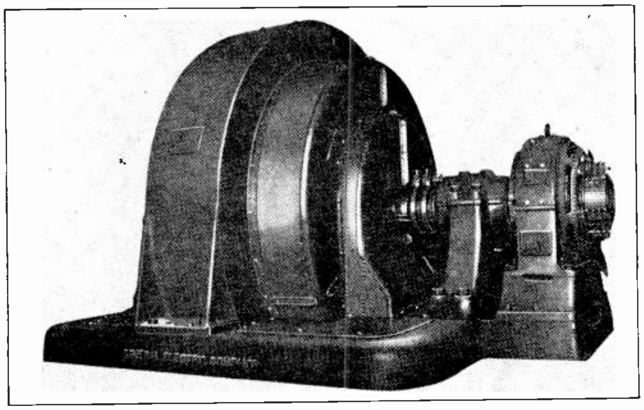

Fig. 212. 5000-kv-a., 2300-volt, enclosed-type, synchronous condenser. The exciter for this machine is shown on the right. (Photo courtesy G. E. Company)

through this casing from openings in the bottom of the frame. The exciter-generator shown is mounted on a separate base on the end of the main condenser base and is driven by the end of the main shaft.

226. STATIC CONDENSERS

The use of static condensers for power-factor correction has become quite general during the last few years. These devices have the advantage of being simple to install and of requiring practically no care or maintenance, as they have no moving or wearing parts.

They are of somewhat higher first cost and have the additional disadvantage of not being adjustable except by changing the number of condenser units which are connected to the system.

Static condensers can be used in large banks or groups to correct the power factor of the entire system, by connecting them at the switchboard or transformer bank where the power enters the plant or buildings. Small condensers can be used to correct the power factor of individual induction motors by connecting them directly to terminals of these motors and locating the condenser within a few feet of the motor itself.

Fig. 213 shows a 300 kv-a. static condenser for operation on 2500 volts. This unit consists of a number of small condensers located in racks and

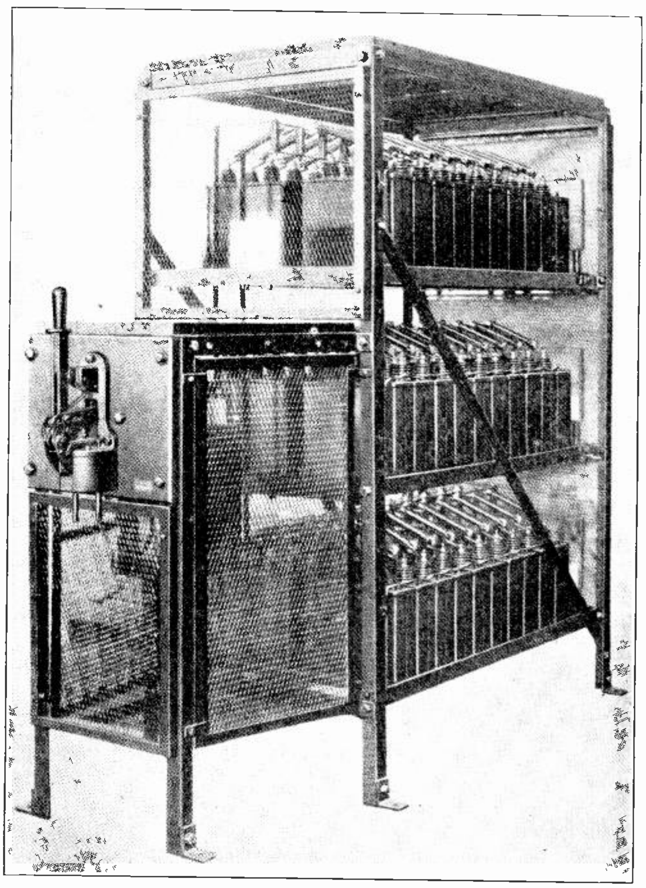

Fig. 213. 300-kv-a., three-phase, 2500-volt, capacitor or static condenser, used for improving power factor. (Courtesy General Electric Co.

properly connected across the three phases of the line. These condensers can be seen mounted in three banks in the three levels of the frame. The oil switch mounted on the front of the unit is for disconnecting the condenser from the system whenever necessary.

Fig. 214 shows a pair of condenser units, or capacitor units as they are often called. These units are equipped with resistors of the cartridge type for discharging them when they are disconnected from the line. If it were not for these resistors shunted across the condensers they would hold a charge of high voltage for a considerable period after being disconnected, and this would make them dangerous for an operator to work on.

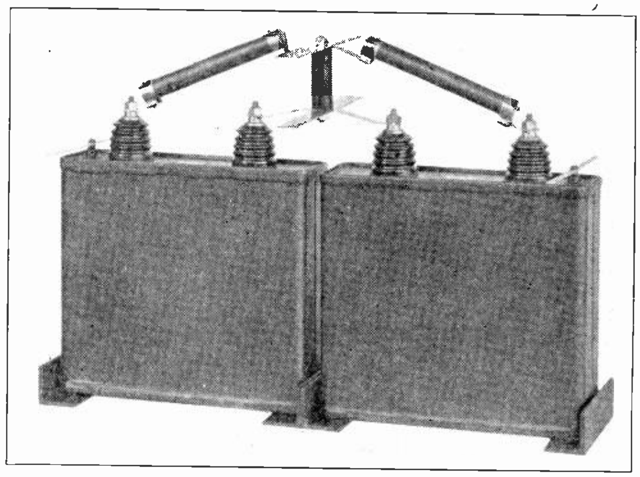

Fig. 214. Two single-phase condenser units connected together with discharge resistors in their circuit. (Courtesy G. E. Company)

It is also advisable to short-circuit any condenser with a piece of insulated wire, to make sure that it is discharged before working on it.

The resistance units are of high enough resistance so that they do not appreciably short-circuit the condensers or cause any considerable loss during operation. When the condensers are disconnected from the line, however, it requires only a few seconds for the energy stored in them to discharge through the resistance units.

227. CONSTRUCTION OF STATIC CONDENSERS

You are already quite familiar with the construction of condensers and have learned that they consist primarily of thin conducting plates of metal foil, separated by sheets of insulation or dielectric of the proper thickness and quality to stand the voltage at which the condenser is designed to operate.

These alternate sheets of metal and insulation can be arranged either in a flat stack with every other metal plate connected to opposite terminals, or in a roll with a good many square feet of each material rolled into one compact unit and these long metal strips then connected in parallel to the terminals.

Fig. 215 shows two views of roll-type condenser units in which the strips of metal foil are rolled between strips of insulating paper. Note the terminals which are brought out on the ends of these units for connecting a number of them in series or parallel to obtain the proper voltage and capacity rating of the condenser.

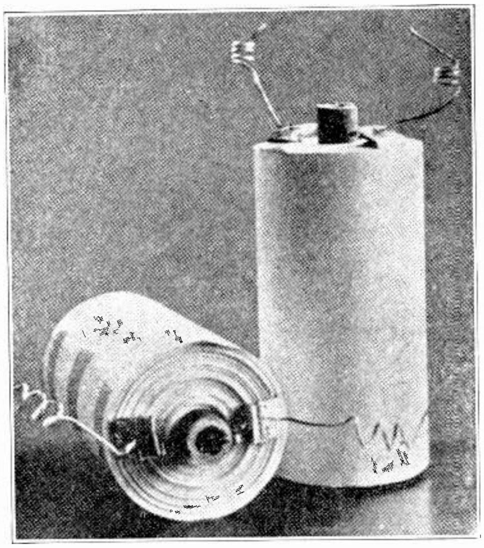

Fig. 215. Roll-type condenser units in which the long strips of metal foil and insulating paper are rolled into one compact condenser element. (Courtesy Electric Machinery Mfg. Co.)

Fig. 216 shows a number of these roll-type condensers mounted in one tank or case and connected three-phase to the terminals in the box on the front of the tank.

The condenser tanks are generally filled with insulating oil or compound to add insulating strength and also to keep out all moisture and thereby preserve the quality of the insulation of the units.

Fig. 217 shows a complete condenser unit with an oil switch mounted on the front of the tank for making and breaking the connections between the condenser and line.

Condensers which are enclosed in water-proof tanks such as shown in Figs. 215 and 216 can be used either indoors or outdoors, and in some cases they are mounted on poles or platforms with the outdoor transformers.

228. OPERATION OF STATIC CONDENSERS

You have already learned that when a difference of potential is applied to the terminals of two parallel conducting surfaces which are located close together but insulated from each other, they will absorb or store up an electro-static charge. When the applied voltage is removed and the condenser short-circuited, this static energy will discharge in the form of dynamic current.

When alternating current is applied to a condenser it charges the unit during the period of the alternation when the voltage is increasing from zero to maximum, and allows the condenser to discharge back into the line when the voltage starts to fall from maximum to zero.

The current thus supplied by the condenser leads the applied line-voltage by approximately 90° and thereby neutralizes the effect of lagging currents in the circuit.

When a condenser is connected to terminals of an induction motor as shown in Fig. 218, the condenser supplies wattless current or magnetizing current to the motor so that this lagging current doesn't flow through the line between the transformers or alternators and the motor.

The opposite characteristics of the induction motor and the static condenser cause a continual circulation or interchange of current between the two during operation. By preventing this flow of wattless current through the lines, the static condenser reduces the voltage drop in the line and in many cases makes possible the use of smaller line or feeder conductors to the motor. It also reduces the amount of wattless current carried by the alternator windings.

229. LOCATION OF CONDENSERS

When the motors are of medium or large size it is often desirable to correct the lagging power

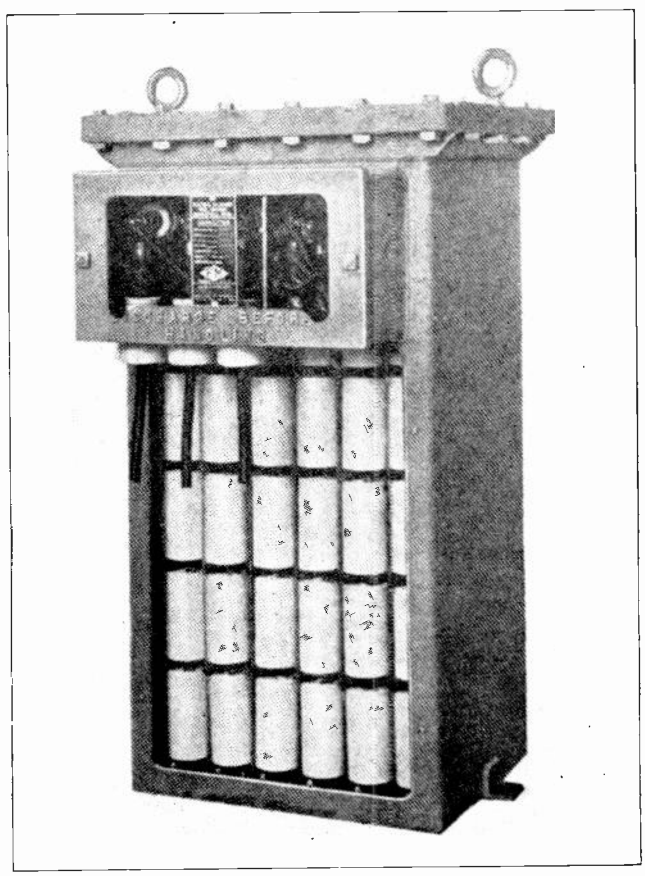

Fig. 216. Complete static condenser with side of tank cut away to show arrangement of roll-type condenser units. (Courtesy Electric Machinery Mfg. Co.)

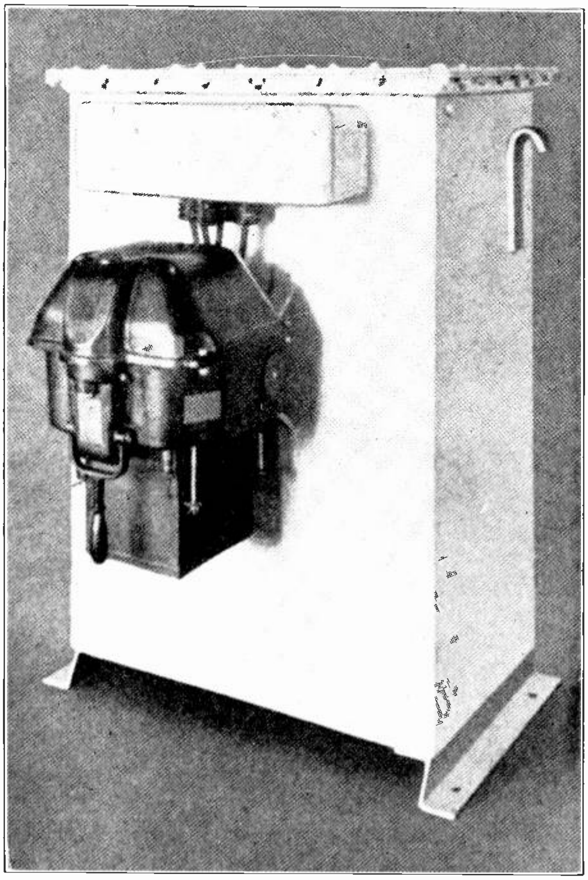

Fig. 217. This photo shows a static condenser enclosed in a moisture-proof metal tank and equipped with an oil switch for breaking the circuit between the condenser and the line. These condensers are made for both indoor and outdoor service. (Courtesy Electric Machinery Mfg. Co.)

factor right at its source by connecting small condensers to the motor terminals. This prevents the flow of wattless current or magnetizing current through the feeders in the plant and through the power line and alternators. In other cases, where this is not convenient and there are a number of small or medium-sized motors connected to the wiring system in a plant, it may be better to attach a large condenser or bank of condensers to the line or feeders at a point as near to the load center as possible.

In many cases the condensers are connected to the secondaries of the transformers which step down the voltage of the alternating current where the power enters the plant or building.

This relieves the transformers, power lines, and alternators at the generating plant from carrying the wattless current, but it doesn't remove this wattless current from the feeders and circuit within the plant where the low power factor exists.

Correcting the power factor in this manner may be satisfactory to the power company and relieve the customer of the penalty charge for low power factor, but it doesn't eliminate the voltage drop and losses which occur in the feeders and circuits of the customer's plant, nor the reduced efficiency of motors and equipment which may result from this voltage drop.

For this reason **it is more desirable to correct the low power factor right at its source by using condensers at the terminals of individual large motors whenever practical.** Where it is not possible or practical to locate condensers at the terminals of large motors or where a large number of small motors are used, it is often more practical to install one large condenser as near as possible to the center of the load, so that it will correct the power factor for a group of small motors and supply the magnetizing current to these machines through the shortest possible length of the feeder wires.

Fig. 219 shows three large motors, each equipped with an individual static condenser connected directly to its terminals and also a number of small motors with one condenser, "D", located approximately at the center of the small motor load. The condensers, A, B, and C, confine the flow of wattless current for the large motors to the short wires between the motors and condensers, and if these condensers are of the proper size, none of the

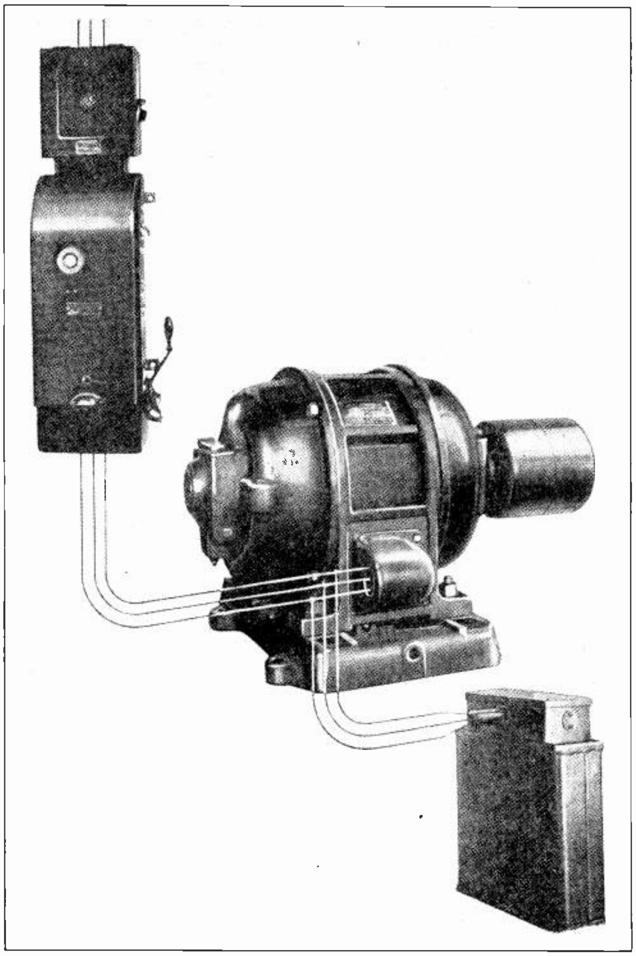

Fig. 218. Static condensers can be connected direct to the terminals of individual induction motors as illustrated in the above view. The condenser then supplies the magnetizing current to the motor and corrects the lagging power factor at its source. (Courtesy G. E. Company)

magnetizing current for these machines will flow through the main feeder wires.

If condenser D is of the proper size to supply the magnetizing or wattless current for all of the small motors, then this wattless current will only flow through a very short section of the main feeders and in this manner will be prevented from causing voltage drop in the longer feeder lines.

Keep in mind, in the case of condenser D, that the wattless current for each of the small motors located near this condenser will only flow between the motors and the condenser.

If, for any reason, it were not desirable to use the small condensers A, B, C, and D distributed throughout this power wiring system, a large condenser could be located at "X", as shown by the dotted lines. While this would not remove the wattless current from the feeders throughout the plant, it would prevent the transformers, power line, and alternator from being overloaded by the wattless current.

In some cases synchronous condensers are used right at the power plant for the sole purpose of relieving the alternators of wattless current. Sometimes an idle alternator can best be used as a synchronous condenser just floating on the busses to supply magnetizing current, instead of using up steam to drive this alternator to make it carry its share of the total effective current and magnetizing current.

230. POWER FACTOR CORRECTION BY PROPER LOADING AND PROPER SELECTION OF MOTORS

Before installing any power factor corrective equipment, such as synchronous or static condensers, it is generally best to do everything possible to improve the power factor by changing or rearranging the existing motors. Lightly loaded induction motors operate at very low power factor.

Very often it will be found that oversize induction motors have been chosen to drive certain machines which require the starting torque of a large induction motor; but which, after they are running, keep this motor loaded at only one-fourth to one-half of its rating.

In such cases it would be better to replace these squirrel-cage induction motors if possible with slip-ring motors or special squirrel-cage motors with better starting torque, so that motors of the proper size can be used and then operated at approximately full load during running.

In many instances it is possible to change motors around so that they are better fitted for the power requirement of the machines they drive, and in such cases it may not be necessary to discard or replace more than a few motors.

In a plant which is largely operated by squirrel-cage induction motors and is known to have a very low power factor, great care should be used in selecting additional motors whenever new equipment is added.

If synchronous motors are used to drive as much as possible of the new equipment or if synchronous motors are installed to drive some of the old equipment which may be better fitted to their characteristics, this will release induction motors from the old equipment to drive the new machines.

On any equipment that cannot be satisfactorily operated by ordinary synchronous motors, it will probably be possible to use special high-torque synchronous motors, or at least to use slip-ring motors in order to get the necessary starting torque with the best possible efficiency and power factor.

When inspecting or changing old motors, or installing new ones in any plant where you may be employed, always keep in mind the great savings which can be effected by the proper selection and proper loading of A. C. motors.

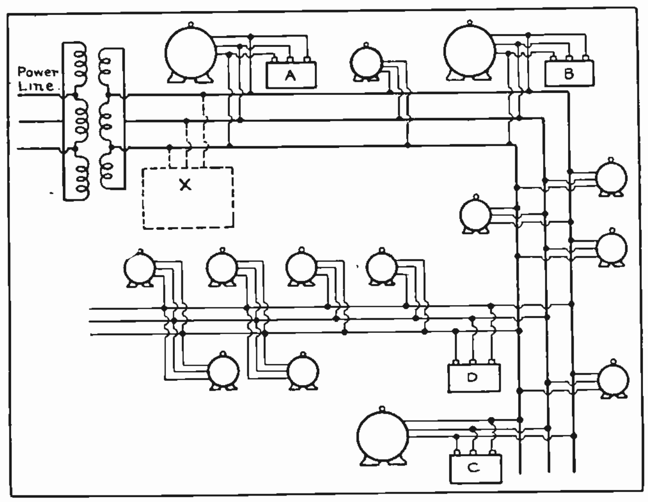

Fig. 219. This diagram illustrates the manner in which condensers can be connected to individual large motors and also at load centers to correct the power factor for a group of small motors.

231. SELECTION OF POWER FACTOR CORRECTIVE EQUIPMENT

When everything possible has been done in this manner, the power factor may still be too low and may be causing serious overloading of existing feeders and circuits and excessive voltage drop at the motors and equipment to be operated. It may also be causing a penalty charge on the power bill or overloading of transformers and alternators in case the company generates its own power. If this is the case then some other means of power factor correction should be considered.

The equipment used for this purpose should not be installed by guess work just because it is known that it will improve the power factor. Instead the entire system should be carefully gone over and tested to determine what the power factor actually is and what the extent of the load is on the alternators, transformers, and feeders in proportion to their capacity.

In many cases it is also advisable to check the power factor on different main branches of the system and the voltage drop at the terminals of equipment in different parts of the plant.

If the power is being purchased, the power bills should also be carefully checked to see how much can be saved by improving the power factor. In this manner the power factor corrective equipment can be intelligently selected to give results where they are most needed and to effect the greatest possible saving.

In determining the type of corrective equipment to use or in choosing between synchronous motors, synchronous condensers or static condensers, further care should be exercised.

If there are in the plant a number of machines or devices which are well suited to synchronous motor drive, and if there is some other use for the induction motors which will be replaced; or if these machines can be profitably sold or are old enough to be discarded, then synchronous motors of the proper size for driving the machinery and also correcting the power factor are generally a wise choice.

If the plant in which the power factor is to be corrected is a large one and has several centers of heavy load at low power factor, the installation of synchronous condensers at these load centers is often advisable.

Before choosing synchronous condensers, however, we should keep in mind that they require the same amount of skilled attention and maintenance that synchronous motors require.

If the plant is of small or medium size and if the motors and loads are widely scattered at the ends of long feeders and circuits, the installation of static condensers properly located throughout the plant may be most economical.

In numerous cases where alternators, transformers, and feeders may be overloaded to the point where it is necessary to replace them with larger ones or to add new ones to operate in parallel, it may be found that a considerable portion of this load is wattless current.

If correcting the power factor will relieve this condition and enable the existing equipment to be used for several years more, it is generally much cheaper to buy power-factor-corrective equipment and save the cost of the new generators and transformers.

Considerable copper cost can also be saved where the feeders or lines are of considerable length.

In some cases where the power is purchased and even though the power contract may not contain a penalty clause for low power factor, it may be possible to obtain a lower power rating or a rebate on the power bills by going to the power company with a definite proposal for improving the power factor of the customer's load to a certain amount.

232. DETERMINING THE PROPER SIZE OF CONDENSER REQUIRED

It is a very simple matter to calculate the actual amount of saving that can be effected by correcting power factor a certain amount, and also to calculate the size of the synchronous condenser or static condenser which will be required to correct the power factor the desired amount.

To determine the proper size of the condenser or the amount of corrective kv-a. required, it is first necessary to note the amount of actual load in kw. and the power factor of this load.

The next step is to decide to what new and higher value the power factor of the load should be raised. Generally it is not economical or practical to try to raise the power factor to unity or 100%, because the closer to unity the power factor is raised the greater will be the amount of corrective kv-a. required to increase the power factor any additional amount. So we reach a point where the very great cost of corrective equipment overbalances the saving and benefits derived from correction.

Furthermore, this unity power factor is not desirable on some systems, because a very small change in the load or power factor when the system is already at unity power factor, results in a considerable change in the current and tends to make the system unstable.

For these reasons a desirable power factor is usually somewhere between 85 and 95 per cent. When the load in kw. and the power factor of the plant or system are known, it is easy to calculate the apparent power in kv-a. and also the **wattless energy** or **reactive kv-a.** This latter is often called the wattless **component**, meaning the wattless portion or part of the energy.

233. PRACTICAL FIELD PROBLEMS

For example, suppose we are considering an industrial plant in which the actual power load is 1440 kw. and we find that the power factor of this load is 60%. This power factor can be determined by tests with voltmeter, ammeter, and wattmeter, or with a power-factor indicator, as explained in an earlier section.

We shall assume that we desire to increase this power factor to 90%. Our first step is to find the kv-a. at the present power factor. This will be:

$$1440 \div .60, \text{ or } 2400 \text{ kv-a.}$$

Now, to find the wattless component or reactive kv-a., we **square both the actual power and the apparent power and then obtain the square root of the difference between these figures.**

This can be stated in the following simple formula:

$$\text{Reactive kv-a.} = \sqrt{\text{kv-a.}^2 - \text{kw.}^2}$$

In the case of the problem we are considering, the reactive kv-a. will be:

$$\sqrt{2400^2 - 1440^2}, \text{ or } 1920 \text{ kv-a.}$$

This is the wattless power at 60% power factor. The next step is to find what the wattless component will be at 90% power factor. This is found in the same manner as we have used for the 60% power-factor condition.

At 90% power factor, the apparent power of the system will be 1440 ÷ .90, or 1600 kv-a.

Note the great reduction in the apparent power which is required to produce the same amount of actual power at the higher power factor. While at 60% power factor it required 2400 kv-a. to produce 1440 kw., at 90% power factor it requires only 1600 kv-a. to produce 1440 kw.

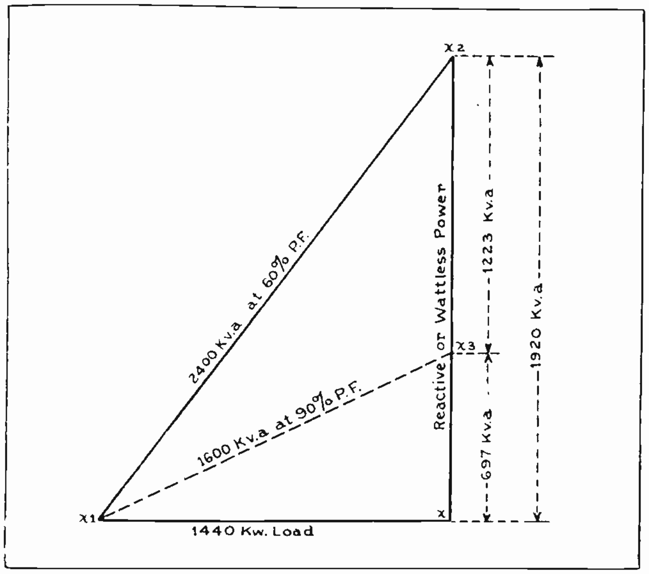

Fig. 220. The above sketch shows the simple method by which power factor problems can be solved graphically by drawing to scale the lines representing the various factors in the problem. Study this diagram very thoroughly with the accompanying explanations.

As we know that the current is proportional to the volt-amperes divided by volts, we can immediately see that the increased power factor will greatly reduce the current flowing in the circuits.

We can now determine what the wattless power or reactive kv-a. will be at the new power factor. This is found by the same formula as previously given, and, in this case, the reactive kv-a. equals:

$$\sqrt{1600^2 - 1440^2}\text{, or 697 kv-a.}$$

If the reactive kv-a., or wattless power, was 1920 at 60% power factor and is now only 697 at 90% power factor, then the difference between these two will be the reactive kv-a. required to increase the power factor from 60 to 90 per cent., or 1920 — 697 = 1223 kv-a.; which will be the capacity of the condenser required to correct the power factor this amount.

In other words, the condenser must have a capacity of 1223 kv-a.

This problem is further illustrated by the diagram in Fig. 220. The horizontal line forming the base of the triangle represents the 1440 kw. of actual power or load. This line is drawn to a scale of 1/8 of an inch per 100 kw.

The vertical line forming the adjacent side of the triangle represents the wattless or reactive kv-a. This line is drawn to the same scale and its full length represents the 1920 kv-a. of wattless power at 60% power factor. The lower section from X to X-3 represents the 697 kv-a. of wattless energy at 90% power factor.

The difference between these two, or the upper section of the line from X-3 to X-2, represents the 1223 kv-a. which will have to be neutralized by an equal amount of leading kv-a. from the condenser.

The long diagonal line from X-1 to X-2, or the hypotenuse of this large triangle, represents the 2400 kv-a. of apparent power at 60% power factor. The lower diagonal line drawn from the point of 697 kv-a. on the reactive power line to the point of the angle represents the 1600 kv-a. apparent power which will be required at 90% power factor.

234. GRAPHIC SOLUTION OF POWER FACTOR PROBLEMS

This same problem can be solved approximately with very few figures by laying out lines carefully measured to the proper length to represent the various values to scale.

For example, let us take a sheet of paper with square corners and, starting at the lower right-hand corner of the sheet as at "X" in Fig. 220, we shall first lay out to the left along the lowest edge of the sheet a line which is the proper length to represent the load in kw. Any suitable scale, such as 1/8, 1/4, or 1/2 inch, can be used to represent 10, 50, or 100 kw., according to the amount of load and the size of the paper available. The larger the scale used, the more accurate the measurements can be made.

If we next determine the apparent power by dividing the kw. load by the known power factor of the system, we can then lay out a line of the proper length to represent this apparent power in kv-a. on the same scale as that used for the base line representing the load in kw.

If we lay out a line of this length on the edge of the ruler or straight strip of paper, and then lay this line from the left end of the kw. line, or X-1, and so that the opposite end of the line falls at the right edge of the sheet of paper at X-2, we can then measure the distance along the edge of the paper from X to X-2, and thus find the wattless or reactive kv-a. for this load and power factor, by measuring this distance on the same scale as we used for both of the other values.

Then if we develop another line to represent the kv-a. of apparent power at 90% power factor and lay this line from X-1 to the edge of the paper at X-3, we can measure from X-3 to X and obtain the approximate reactive kv-a. at the improved power factor.

235. SAVING EFFECTED BY POWER FACTOR IMPROVEMENT

In the problem we have just considered, we find that increasing the power factor from 60 to 90 per cent. reduces the apparent power from 2400 to 1600 kv-a. This is a reduction of 800 kv-a. or, in other words, the alternators, lines, and transformers can supply the same actual power with a reduction of 800 kv-a. load on their windings.

If the greater part of this energy is fed throughout the customer's plant at 440 volts, this will mean considerable reduction of the current load on the feeders.

This can be determined as follows:

volt-amperes $\div$ (E $\times$ 1.732)

or

800,000 $\div$ (440 $\times$ 1.732) = 1049 amperes

Increasing the power factor will also reduce the current load by the same amount in the 440-volt secondaries of the transformers at the customer's premises.

If this energy is supplied to the primaries of the transformers by a 2300-volt distribution line from the power company's substation, the current on this line and primary winding of the transformers will be approximately 200 amperes less.

Of course, the actual reduction in current will not be quite this great if a synchronous motor is used for the power factor correction, because this machine will require a small amount of energy current to overcome the friction and windage-loss of the machine. This amount, however, is so small that it is hardly worth considering.

In case a static condenser is used for power-factor correction in this problem, the loss will also be extremely small; as the loss of this device is generally less than ½ of 1%.

The method used to calculate the capacity of either a synchronous condenser or static condenser is the same, as long as the synchronous condenser is used only for power factor correction and not to drive any mechanical load.

To see the great importance of having a proper knowledge of power factor and its correction, we need only to note the amount of saving that can be effected by power factor improvement in the problem we have just considered.

The great reduction made in the current load on the transformers, lines, and alternators might enable a plant to avoid the installation of new transformers and alternators, and take care of expansion and growth for possibly several years longer, by this correction of power factor.

Considering it from the standpoint of monthly power bills in case the power is purchased from a generating company, the saving is also considerable.

For example, if the 1440 kw. load which was used in this problem is taken to be the average load throughout an eight-hour day in the plant of the customer, the total power consumed in one month of 26 working days would be 299,520 kw. hours.

At a cost of approximately 1 cent per kw. hour, the monthly power bill would be $2,995.20. If the power company from whom this energy is purchased has a power-factor-rate clause in the contract, it is possible that the reduction in the rate between the 60% and 90% power factor conditions would be as much as 10% of the power bills.

This would result in a monthly saving of $299.52, or a yearly saving of $3,594.24. So we find that this would soon pay for the cost of a 1223 kv-a. synchronous condenser at approximately $6,000.00.

236. PROBLEM

As another illustration, suppose you are working as maintenance electrician in an electrical plant where the total load of induction motors, welders, and electrical ovens amounts to 560 kw. Let us assume that this is the normal true-power load shown by the wattmeter under average operating conditions in the plant.

If this energy is fed to the motors and equipment at 440 volts and a total of the ammeter readings on the different feeder circuits shows the current load to be approximately 1130 amperes, then the apparent power is equal to 440 $\times$ 1130 $\times$ 1.732, or approximately 861 kv-a.

Then, to determine the power factor of the system, we divide the true power by the apparent power, or 560 $\div$ 861 = approximately 65% power factor.

We shall assume that you wish to raise this power factor to 90%. The present load in kw. can again be represented by the horizontal base line of the triangle in Fig. 221.

In this figure a scale of ½ inch to 100 kw. is used. Now, assuming that the vertical line is the right-hand edge of a square sheet of paper and that the base line is on the lower edge of this same sheet of paper, we will lay out a line to the scale of ½ inch per 100 kv-a. and of the proper length to represent the 861 kv-a. of apparent power.

Running this line from the point X-1 at the left end of the kw. line to X-2 at the right edge of the paper, we have represented the apparent power by the hypotenuse of the triangle.

Now, if you measure the line from X-2 to X-3, you will find it is slightly over 3¼ inches long and, on the basis of ½ inch per 100 kv-a., this will equal approximately 654 kv-a. of wattless, or reactive, power. This we have marked "R kv-a.".

Now, to find the amount of reactive kv-a. or wattless power which we will have when the power factor is improved to 90%, we must first determine the total kv-a. of apparent power at 90% power factor.

True power $\div$ power factor = apparent power, so,

560 $\div$ .90 = approximately 622 kv-a. apparent power at 90% p. f.

Using the scale of ½ inch per hundred kv-a., we shall represent the 622 kv-a. with a line slightly under 3⅛ inches long. Marking off this line on the edge of a ruler or straight piece of paper, set one end of the line at X-1, and swing the other end over to the point where it touches the right edge of the paper, or line X-2 to X-3. We find that the end of the line meets the vertical line at X-4.

Now measuring the portion of the vertical line from X-4 to X-3, we find that it represents approximately 271 reactive kv-a. according to the same scale of ½ inch per 100 kv-a.

Now, to determine the amount of corrective kv-a. required, we subtract 271 from 654 and find 383 R kv-a., which is the amount to be corrected and which will be the required capacity of the synchronous or static condenser to use for this job.

We can now check these figures by the more accurate method, using the formula:

$$\text{R kv-a.} = \sqrt{\text{kv-a.}^2 - \text{kw.}^2}$$

with which we obtained the values in the previous problem.

In the first condition, with 65% power factor and 861 kv-a., the total reactive kv-a. or wattless power will be:

$$\sqrt{861^2 - 560^2}, \text{ or } 654$$

$861^2 = 741{,}321$

$560^2 = 313{,}600$

and $741{,}321 - 313{,}600 = 427{,}721$.

The square root of 427,721 is 654; so we find that the value of the reactive kv-a. shown by the vertical line from X-2 to X-3 is correct.

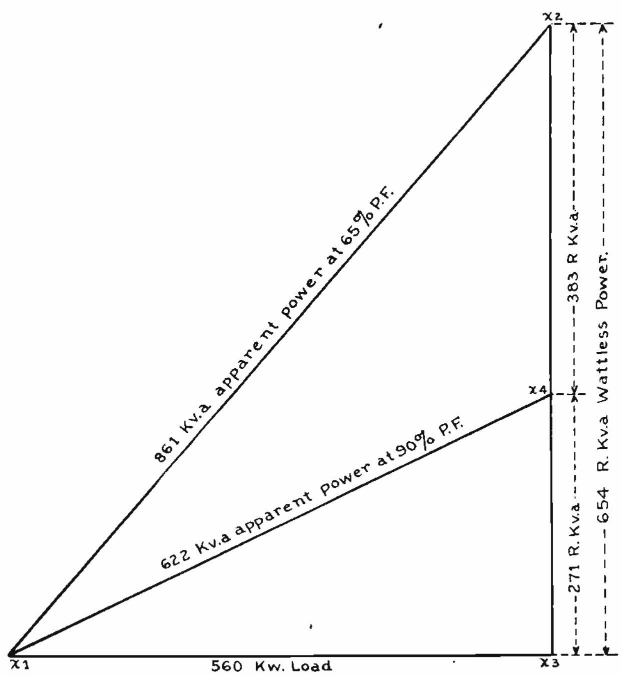

Fig. 121. This diagram also shows the reduction obtained in the apparent power and wattless power by improving the power factor of a system. By carefully measuring the top section of the vertical line in the diagram we can find the size of the condenser required to correct the power factor.

We shall next find the reactive kv-a. at 90% power factor; which will be:

$$\sqrt{622^2 - 560^2}, \text{ or } 271 \text{ R kv-a.}$$

$622^2 - 386{,}884$

$560^2 - 313{,}600$

$386{,}884 - 313{,}600 = 73{,}284$

The square root of 73,284 is approximately 271, which proves that the value of the reactive kv-a. shown by the vertical portion of the line from X-4 to X-3 is also correct.

With just a little practice to get the steps of these power factor problems well in mind, you will find it very simple to determine the size of condenser required for correcting the power factor of any given load at low power factor and to bring it up to the desired higher power factor.

It will be well worth your time to practice both the approximate method with the triangle diagram and also the accurate method using the formula.

By improving the power factor from 65% to 90% in the plant we have considered in this last problem, we shall have reduced the apparent power from 861 to 622 kv-a. or by 239 kv-a. This means that the alternators, transformers, and feeders will be relieved of this amount of load. On the 440-volt feeders this will amount to approximately 314 amperes, as can be determined by the following formula:

$$I = \frac{\text{volt-amperes}}{E \times 1.732}$$

or, in this case,

$$I = \frac{239{,}000}{440 \times 1.732}, \text{ or } 314 - \text{amperes}$$

You can readily see that relieving the feeder cables of this amount of current would decrease the voltage drop in them considerably—especially if they were already overloaded at the low power factor. Relieving the transformers of this load would enable them to carry an increased load of useful power; and the same thing applies to the alternators of the power company, or the alternator which may be owned and operated by your employer if the plant in which you work generates its own power.

237. USE OF SYNCHRONOUS MOTORS FOR P. F. CORRECTION AND MECHANICAL LOAD

When it is desired to use a synchronous motor both for driving a certain amount of mechanical load and for correcting the power factor of the load already on the system, we must, of course, allow sufficient capacity of the machine for both of these duties. The actual problem or calculation, however, remains very much the same.

Let us assume that in a certain plant there is an existing load of 600 kw. at a power factor of 60%. We wish to improve this power factor of 90% by the use of a synchronous motor and we also wish to operate with this motor a new mechanical load of 300 kw.

We shall represent the existing load by the horizontal line from X to X-1 in Fig. 222, and the additional new mechanical load of 300 kw. by the addition to this line from X-1 to X-2. The scale in this diagram is ¼ inch per 100 kw.

At 60% power factor the apparent power of the existing load will be 600 ÷ .60, or 1000 kv-a.

We shall represent this kv-a. by the same scale of ¼ inch per 100 kv-a. and by a line 2½ inches long, running from X to a point where its opposite end strikes a vertical line which we have drawn up from the base line at X-1.

This hypotenuse line, representing the 1000 kv-a. of apparent power, will strike the vertical line at X-3, and if we measure the line from X-3 to X-1, we find it is two inches long. On the same scale used for the other values, it will therefore represent 800 R kv-a. of reactive or wattless power.

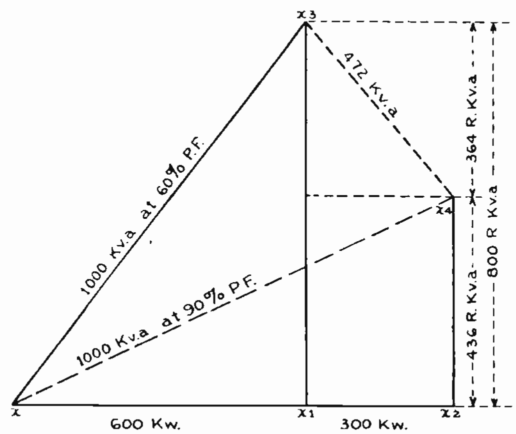

Fig. 222. This diagram shows the graphic solution of a problem in which the synchronous motor is used for mechanical power purposes as well as power factor correction. The figure should be easily understood by referring to the explanations in the accompanying paragraphs.

Checking this calculation by the more accurate method of using the formula:

$$R\ kv\text{-}a. = \sqrt{1000^2 - 600^2}$$

we find the answer is exactly 800 kv-a.

The next step will be to determine the kv-a. of apparent power of the existing load plus the new mechanical load at the desired power factor of 90%. The entire load will be 900 kw., and at 90% power factor the kv-a. will be:

900 ÷ .90, or 1000 kv-a.

It is interesting to note at this point that with the improved power factor we can obtain a 50% increase in the true power load with the same kv-a. as existed with the 600 kw. load.

Representing this 1000 kv-a. on the scale of ¼ inch per 100, or by a line 2½ inches long, we shall first run this line from X to the point where it strikes a vertical line above X-2. This vertical line from X-2 to X-4 will represent the reactive kv-a., or wattless component, for the entire load of 900 kw.

Measuring this line to scale, we find that it represents approximately 436 reactive kv-a.

We shall now check this figure by the more accurate method with the formula:

$$R\ kv\text{-}a. = \sqrt{1000^2 - 900^2}, \text{ or } 436 — R\ kv\text{-}a.$$

Subtracting this from the former reactive kv-a., we find 800 — 436 = 364 R kv-a., which must still be corrected to bring the power factor to 90%.

The capacity of the synchronous motor must therefore be:

$$\sqrt{300^2 + 364^2}, \text{ or } 472 — kv\text{-}a.$$

This capacity or kv-a. of the synchronous motor can also be found by measuring the distance from X-3 to X-4, as shown by the dotted line in Fig. 222, and using the same scale of ¼ inch per 100 kv-a.

The power factor rating of the synchronous motor, or the power factor at which it will need to operate to carry this mechanical load and also correct the reactive kv-a., will be found by dividing its true power or mechanical load by its total kv-a. rating, or:

300 ÷ 472 = approximately 64% leading power factor.

237-A. TABLE FOR DETERMINING REQUIRED SIZE OF CONDENSERS

The convenient table in Fig. 223 greatly simplifies the method of determining the proper capacity of the synchronous or static condenser to correct the power factor a certain desired amount for any given load.

This table gives figures which can be used as constants to be multiplied by the kw. load to obtain the leading reactive kv-a. required to improve the power factor from one value to another.

For example, if the kw. load, as indicated by the wattmeter in a plant, is 200 kw. at an existing power factor of 65% and we desire to increase the power factor to 90%, we look in the table under the column heading "Original Power Factor" and find 65; then, reading to the right under "Desired Power Factor" in the column for 90%, we find the figure .685.

We now simply multiply this figure by the load in kw., or:

200 × .685 = 137 kv-a. capacity

or the size of condenser required to bring lagging power factor from 65 to 90 per cent.

If, in another case, we have a load of 525 kw. at a power factor of 70% and we wish to increase the power factor to 85%, we find in the middle column under "Original Power Factor", the figure 70. Then, reading to the right in the fourth column under "85% Desired Power Factor", we find the figure .400. Multiplying this figure by our load of 525 kw. gives 210 kv-a. as the required size of the condenser.

ORIGINAL POWER FACTOR %	DESIRED POWER FACTOR 100 %	95 %	90 %	85 %	80 %	ORIGINAL POWER FACTOR %	DESIRED POWER FACTOR 100 %	95 %	90 %	85 %	80 %
20	4.899	4.570	4.415	4.279	4.149	61	1.299	.970	.815	679	549
21	4.656	4.327	4 171	4.036	3.906	62	1.266	.937	.781	.646	.515
22	4.433	4.104	3.949	3.813	3.683	63	1 233	.904	.748	.613	.482
23	4.231	3.902	3.747	3.611	3.481	64	1.201	.872	716	581	.450
24	4.045	3.716	3.561	3.425	3.295	65	1.169	.840	.685	.549	.419
25	3.873	3.544	3.389	3.253	3.123	66	1.138	.810	.654	.518	.388
26	3.714	3.385	3.229	3.094	2.964	67	1.108	.779	.624	.488	.358
27	3 566	3.238	3.082	2.946	2.816	68	1.078	.750	.594	.458	.328
28	3.429	3.100	2.944	2.809	2.679	69	1.049	.720	.565	.429	.298
29	3.300	2 971	2.816	2.680	2.559	70	1.020	.691	.536	.400	.270
30	3.180	2 851	2.693	2.530	2 420	71	.992	.663	.507	372	.241
31	3.067	2.738	2.583	2.447	2.317	72	.964	.635	.480	.344	.214
32	2.961	2.632	2 476	2.341	2.211	73	.936	.608	.452	.316	.186
33	2.861	2.532	2.376	2.241	2.111	74	.909	.580	.425	.289	.158
34	2.766	2.437	2.282	2.146	2.016	75	.882	.553	.398	.262	.132*
35	2.676	2.347	2.192	2.056	1.926	76	.855	.527	.371	.235	.105
36	2.592	2.263	2.107	1.972	1.842	77	.829	.500	.344	.209	.078
37	2.511	2.182	2.027	1.891	1.761	78	.802	.474	.318	.182	.052
38	2 434	2.105	1.950	1.814	1.684	79	.776	.447	.292	.156	.026
39	2.361	2.032	1.877	1.741	1.611	80	.750	.421	.266	.130	
40	2 291	1 963	1.807	1.671	1.541	81	.724	.395	.240	.104	
41	2.225	1.896	1.740	1.605	1.475	82	.698	.369	.214	.078	
42	2.161	1.832	1.676	1.541	1.410	83	.672	.343	.188	.052	
43	2.100	1.771	1.615	1.480	1.349	84	.646	.317	.162	.026	
44	2.041	1.712	1.557	1.421	1.291	85	.620	.291	.136		
45	1 985	1 656	1.501	1.365	1.235	86	.593	.265	.109		
46	1.930	1.602	1 446	1.310	1.180	87	.567	.238	.082		
47	1.877	1.548	1.392	1 257	1.128	88	.540	.211	.056		
48	1.828	1.499	1.343	1.208	1.077	89	.512	.183	.028		
49	1.779	1.450	1.295	1.159	1.029	90	.484	.155			
50	1.732	1.403	1.248	1.112	.982	91	.456	.127			
51	1.687	1.358	1.202	1.067	.936	92	.426	.097			
52	1.643	1.314	1.158	1.023	.892	93	.395	.066			
53	1.600	1.271	1.116	.980	.850	94	.363	.034			
54	1.559	1.230	1.074	.939	.808	95	.329				
55	1.518	1.189	1.034	.898	.768	96	.292				
56	1.479	1.150	.995	.859	.729	97	.251				
57	1.442	1.113	.957	.822	.691	98	.203				
58	1.405	1.076	.920	.785	.654	99	142				
59	1.368	1.040	.884	.748	.618	100					
60	1.333	1.004	.849	.713	.583						

Fig. 22. The above table gives some very convenient figures by which we can simply multiply the kw. load of a plant with lagging power factor in order to obtain the amount of leading kv-a. or condenser capacity required to correct the power factor any desired amount.

238. PROBLEM

Next, suppose that you have an induction motor on which a wattmeter shows 41 kw. input during operation of the motor at its normal load; a voltmeter shows 220 volts at the motor terminals; and an ammeter shows approximately 144 amperes in any one of the three phase leads to the motor. To determine the power factor at which the motor is operating we must first determine the kv-a. input.

Three-phase kv-a. $= I \times E \times 1.732$

or, in this case,

$144 \times 220 \times 1.732 = 54{,}869$, or approximately 54.9 kv-a.

Now, to determine the power factor of the motor, we can divide the true power input by the apparent power, or:

$41 \div 54.9 = .75$ power factor.

Let us say that we wish to raise the power factor of this motor to 95%. Then, from the table in Fig. 223 we select the power factor of the motor, or 75, found in the middle column under "Original Power Factor"; then, in the column under "95% Desired Power Factor", we find the corresponding figure, .553.

To determine the size of static condenser required to make this power factor improvement on the motor, we simply multiply .553 by the kw. input of the motor, or 41; and this gives 22.67 kv-a. for the condenser. Connecting a condenser of this size to the motor terminals doesn't actually improve the power factor of the motor within the motor itself, but it does bring the power factor of the two units in parallel to 95% on the feeder to which they are connected.

239. CONDENSER TABLE

Fig. 224 shows another convenient table which gives the approximate sizes of condensers required for use with squirrel-cage induction motors to bring their power factors up to either 90% or 95%, as may be desired.

Of course, the power factors of various types of squirrel-cage motors vary considerably; so these figures are necessarily only approximate. They are usually close enough, however, for the selection of condensers to use with motors that normally operate at loads between 50% and 100% of their full-load rating.

This table gives the condenser sizes for motors from ½ h.p. to 200 h.p. at various speeds, and at both the ordinary low and high voltages. Referring to this table, we find that to increase the power factor of a 30-h.p., 440-volt, 1800 r.p.m. motor to 90% we require a 3-kv-a. condenser, and that it will require a 5-kv-a. condenser to bring this power factor up to 95%.

Capacitor Kv-A. for Squirrel-Cage Induction Motors
(To correct to .95 or .90 at one-half load)

MOTOR H. P.	Volts	Capacitor Kv-A. for Desired Power Factor .95	.90
1800 R. P. M.			
½	Low	½	½
¾	Low	½	½
1	Low	½	½
1½	Low	¾	½
2	Low	¾	½
3	Low	1	¾
5	Low	1½	1
7½	Low	2	1½
10	Low	2	1½
15	Low	3	2
20	Low	4	2
25	Low	4	3
25	2200	4	3
30	Low	5	3
30	2200	7½	4
40	Low	7½	4
40	2200	7½	4
50	Low	7½	5
50	2200	7½	5
60	Low	7½	5
60	2200	10	7½
75	Low	10	5
75	2200	10	7½
1200 R. P. M.			
½	Low	½	½
¾	Low	½	½
1	Low	½	½
1½	Low	¾	¾
2	Low	1	¾
3	Low	1½	1
5	Low	2	1½
7½	Low	3	1½
10	Low	3	2
15	Low	4	3
20	Low	5	4
25	Low	7½	5
25	2200	7½	5
30	Low	7½	5
30	2200	10	7½
40	Low	10	7½
40	2200	10	7½
50	Low	7½	5
50	2200	10	7½
60	Low	10	7½
60	2200	10	7½

MOTOR H. P.	Volts	Capacitor Kv-A. for Desired Power Factor .95	.90
1200 R. P. M.			
75	Low	10	7½
75	2200	10	7½
900 R. P. M.			
½	Low	1	1
¾	Low	1	1
1	Low	1	1
1½	Low	1½	1
2	Low	1½	1½
3	Low	2	1½
5	Low	3	2
7½	Low	3	3
10	Low	4	3
15	Low	5	4
20	Low	5	5
20	2200	10	7½
25	Low	7½	5
25	2200	10	7½
30	Low	10	7½
30	2200	10	7½
40	Low	10	7½
40	2200	10	7½
50	Low	15	10
50	2200	15	10
60	Low	15	10
60	2200	15	10
75	Low	15	10
75	2200	15	10
100	Low	20	10
100	2200	20	10
125	Low	25	20
125	2200	30	20
150	Low	25	20
150	2200	25	20
200	Low	30	15
200	2200	35	20
720 R. P. M.			
5	Low	2	2
7½	Low	4	4
10	Low	4	3
15	Low	5	4
20	Low	7½	5
25	Low	10	5
30	Low	10	5
30	2200	15	10

MOTOR H. P.	Volts	Capacitor Kv-A. for Desired Power Factor .95	.90
720 R. P. M.			
40	Low	10	7½
40	2200	15	15
50	Low	15	10
50	2200	15	10
60	Low	20	15
60	2200	20	20
75	Low	20	15
75	2200	25	20
100	Low	30	20
100	2200	25	20
125	Low	30	20
125	2200	30	20
150	Low	35	25
150	2200	40	35
200	Low	35	20
200	2200	40	25
600 R. P. M.			
5	Low	4	3
7½	Low	5	4
10	Low	5	5
15	Low	7½	5
20	Low	10	7½
25	Low	10	7½
25	2200	20	15
30	Low	10	7½
30	2200	20	15
40	Low	15	10
40	2200	20	15
50	Low	20	15
50	2200	20	15
60	Low	20	15
60	2200	25	20
75	Low	25	20
75	2200	40	30
100	Low	20	15
100	2200	25	20
125	Low	30	20
125	2200	35	30
150	Low	50	40
150	2200	50	50
200	Low	50	35
200	2200	50	40

Low means 220, 440, or 550 volts.

Table above gives the nearest standard capacitor kv-a. ratings to correct power factor of squirrel-cage induction motors to .95 or .90. Although the magnetizing current requirement of the induction motor varies somewhat from no load to full load, if the motor is corrected to the desired power factor at ½ load (values in the table above) it will be corrected approximately to this power factor at all loads. Actually the power factor will be somewhat higher at no load and slightly lower at full load.

Inasmuch as the power-factor characteristics of induction motors of the same rating vary considerably with different manufacturers the values above are necessarily approximate. The capacitor sizes indicated will be proper however, in the majority of cases.

Fig. 224. This table gives the approximate sizes of condensers required for use with individual squirrel-cage motors to correct the power factor to either 90 or 95 per cent. as desired. It will be well worth your time to become thoroughly familiar with the use of this table and the one in Fig. 223.

A 30-h.p., 2200-volt motor requires a 4-kv-a. condenser to increase its power factor to 90%; or a 7½-kv-a. unit to increase the power factor to 95%.

The discussion of power factor correction which has been given in this section, and also the examples of practical problems and calculations along with the convenient tables, should be given very careful consideration and you should not leave this subject until you are quite sure that you have a good general understanding of the application of these principles and calculations to problems which you may encounter in the field.

In a great number of industrial plants, factories, and other places where electric power equipment is in use and where you may be employed, the owners or even the men in charge of the electrical work may not realize the importance of power factor or the great amount of savings which can in many cases be effected by improving the power factor.

It is not uncommon to find plants with loads of several thousand kw. operating at a power factor ranging from 50 to 90 per cent. In some cases feeder conductors are seriously overloaded and transformers and alternators are overloaded and operating at excessive temperatures, which can be avoided by improving the power factor.

In other cases transformers, alternators, or feeders may be loaded to their utmost capacity and the management may be planning to install additional units and circuits.

If the power factor of the system is very low, it may be possible to avoid the expense of the new alternators and transformers by installing power-factor corrective equipment of much lower cost than new machines. This is particularly true in cases where the company generates its own power and the addition of another alternator would also require added boiler-plant capacity and a turbine or engine to drive the alternator.

The trained man very often has splendid opportunities to suggest and lay out the method of correcting power factor in the plant where he is employed and thereby saving substantial sums for his employer.

For this reason, we suggest you review this material and be sure to keep it well in mind for reference and to use in any job where you may have a chance to apply it to your employer's advantage and your own credit.

NOTES

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ALTERNATING CURRENT POWER
AND
A. C. POWER MACHINES

Section Six

Rectifiers and Converters
Vibrating, Electrolytic, Electronic, Copper Oxide and Mercury Arc Rectifiers
Construction, Operation, Care, Applications
Synchronous Converters
Construction, Operating Principles, Characteristics
Voltage Ratios, Voltage Control
Starting and Operating, Auxiliaries, Care
A. C. Motor Controls
Types, Applications and Advantages of Each
Resistance, Auto Transformer and Drum Types
Manual, Automatic and Remote Controllers
Connections and Circuits. Protective Devices
Installation, Care and Maintenance

RECTIFIERS AND CONVERTERS

While the greater part of the electrical energy used today is generated and transmitted in the form of alternating current, there are a number of special power uses which require direct current.

In plants where a large amount of D.C. is used, it is often produced in this form by D.C. generators, as previously explained. In other cases, where it is cheaper to buy A.C. from a power company or where only very small amounts of D.C. are required, it is common practice to rectify or convert A.C. to D.C.

The most common devices used for this purpose are rectifiers, converters, and motor-generators.

There are several types of rectifiers in common use. These are as follows: **Vibrating, Electrolytic, Electronic, Oxide Film** and **Mercury Vapor.**

The vibrator, electrolytic, and bulb types of rectifiers are generally used only for converting small amounts of energy to D.C., for such work as battery charging, and furnishing D.C. for radio sets, electromagnets, D.C. arc lights, bell and signal systems, experimental and laboratory work, etc.

Mercury arc rectifiers are used in small sizes for the above purposes, and also in large sizes of 1000 kw. and more for supplying D.C. to electric railways, etc.

Rotary converters are also used for changing A.C. to D.C. and are made in large sizes from 100 kw. to several thousand kw., for supplying D.C. to railways and for industrial-power motors, and equipment.

Motor-generators are sometimes used in large sizes of several thousand kw. for supplying D.C. for steel mill motors and such uses, where the service and load variations are very severe; and in smaller sizes for arc welding, etc.

240. VIBRATING RECTIFIERS

Vibrator-type rectifiers are generally used only on low voltages and very small currents. One of their disadvantages is that they have a number of wearing parts and require considerable care and maintenance.

These vibrating rectifiers are synchronous switching devices which reverse the circuit connections at each reversal or alternation of the A.C. supply. They generally operate by the repulsion and attraction of a permanent magnet armature by a pair of A.C. electro-magnets. The moving armature operates the contacts which rapidly reverse the connections of the circuit.

Fig. 225 shows a diagram of the connections and parts of a common type of vibrating rectifier. This rectifier is shown connected to a low-voltage battery which, of course, requires direct current to charge it.

The transformer, T, steps down the voltage from the 110-volt A.C. line to the proper value for operating the magnets of the rectifier and charging the battery.

As the alternating current reverses through the coils of the two electro-magnets M and M-1 which are both wound in the same direction, the polarity of these magnets is rapidly reversed and causes the permanent-magnet armature to vibrate back and forth in synchronism with the alternations of the current.

The secondary of the transformer is provided with a center tap and only half of its winding is used to magnetize the coils. Only half of this winding is used at any instant to charge the battery.

241. OPERATION

When the right-hand end of the secondary is positive, both magnets will have north poles on their lower ends; and the right-hand end of the armature will be repelled, closing the circuit at the adjustable contact X-1.

This allows current to flow from the right-hand end of the transformer winding through resistance R-1, contacts at X-1 through the armature, and to the positive terminal of the battery. This current returns from the negative side of the battery to the center tap of the transformer secondary, thus completing the charging circuit.

Direct current doesn't flow through the small condensers C and C-1 which are merely shunted across the contacts to prevent arcing and burning of the points.

When the alternating current reverses and the left-hand end of the transformer secondary is positive, the lower ends of both electro-magnets will then be south poles and the left-end of the armature will be repelled, closing the contact at X.

The current then flows from the left-end of the transformer secondary through resistance R, contact X, and armature A, to the positive side of the battery, and again returns from the negative terminal of the battery to the center tap of the transformer winding.

The resistance R-2 is used to adjust the strength of the electro-magnets.

You will note that with this type of rectifier both halves of the cycle are used in charging the battery; so it is known as the "full wave" type.

The pulsating direct current always leaves the armature terminal and re-enters the center tap of the secondary winding, so that with a rectifier of this type it is important to get the battery connected with the proper polarity in order to charge it.

Some vibrating rectifiers have a small winding around the movable armature and connected to the terminals which lead to the battery, as shown by the dotted lines in this diagram. This winding reverses the polarity of the armature in case the battery is reversed and thereby makes the direct current flow through the battery in the proper direction, regardless of which way it is connected.

A number of vibrating rectifiers are made, and some of them use different connections and arrangement of parts than those mentioned, but in general their principles are all very much alike.

The high speed at which the armature is required to vibrate and the continual opening and closing of the contacts causes them to become worn and in some cases burned and pitted by the arc formed when the current is interrupted.

For this reason the contacts may require frequent cleaning and adjustment if the rectifier is used for very long periods.

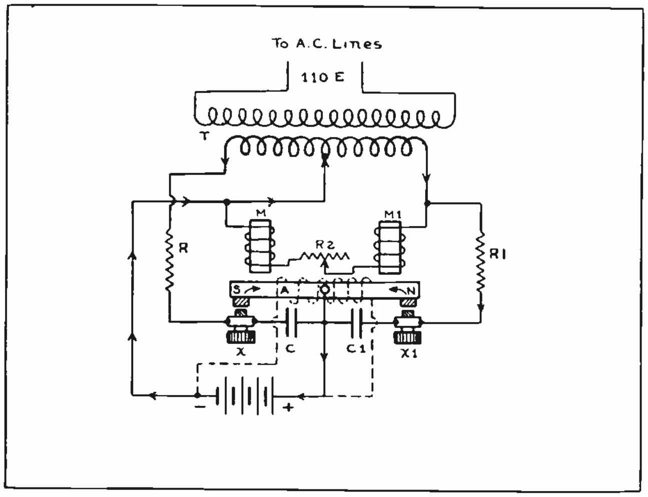

Fig. 225. The above diagram shows the parts and connections of a simple mehanical rectifier of the vibrating type. The synchronous operation of the contacts delivers pulsating D.C. to the battery circuit.

242. ELECTROLYTIC RECTIFIERS

The electrolytic type of rectifier is also limited to small capacities, due to its low efficiency and general tendency to heat up under load because of the large resistance losses which take place within the rectifier itself.

Fig. 226-A shows a simple electrolytic rectifier connected in series with a lamp bank to limit the current flow, and in series with the battery which is to be charged by the pulsating current.

This type of rectifier consists of a jar containing a strong solution of ammonium phosphate, sodium phosphate, or just a mixture of water and common borax. In this solution are immersed a plate of either lead, carbon or iron, and one of aluminum.

The electrolytic action which is set up between the surface of the aluminum electrode and the electrolyte solution will allow the current to flow from the solution into the aluminum, but will immediately build up a very high resistance film when the current is reversed and tries to flow from the aluminum into the electrolyte.

This high-resistance film shuts off the greater part of the current flow during every other alternation, and thus allows the impulses of current to get through the rectifier in only one direction; so that the current applied to the battery is pulsating D.C.

A lamp bank consisting of several lamps in parallel, or some other form of resistor, is often used in series with these rectifiers to limit the current to the proper low value.

The resistance of the rectifier itself is often so low that if it and the battery were connected in series across the line it would result in practically a short circuit and blow the fuses.

243. HALF WAVE AND FULL WAVE RECTIFIERS

A rectifier such as shown in Fig. 226-A uses only every other alternation and is therefore known as a **half-wave rectifier.** This is because the current flow in one direction is blocked except for a small amount of leakage which is required to build up the resistive film on the electrodes.

Fig. 226-B shows another electrolytic rectifier which is of the full-wave type and in which both alternations are used to supply impulses in the same direction through the battery. With this device an auto transformer or choke coil is connected across the 110-volt leads and equipped with taps near the ends of its winding, so that the voltage applied to the rectifier and battery can be varied or adjusted.

When the left end of the transformer is positive, current will flow through that half of the auto transformer winding to the center tap, where a part of the current branches off through the battery and through the rectifier cell from the lead or carbon electrode to the aluminum electrode on the right, and then back to the right-hand line wire. No current can flow from the left-hand line wire

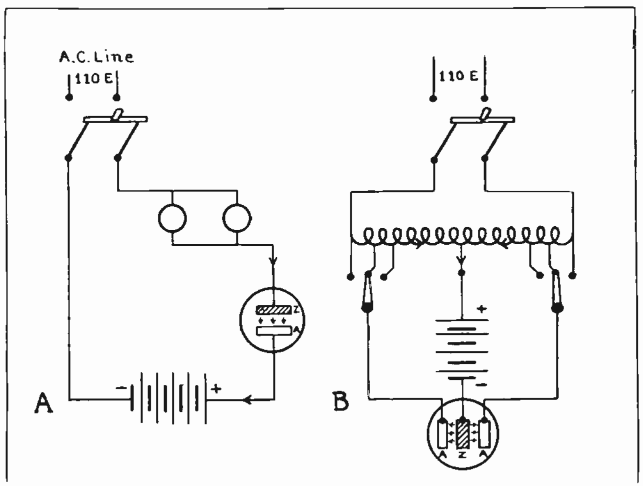

Fig. 226-A. Shows a half-wave, electrolytic rectifier and B shows an electrolytic rectifier of the full-wave type. Current can only pass through these devices in one direction.