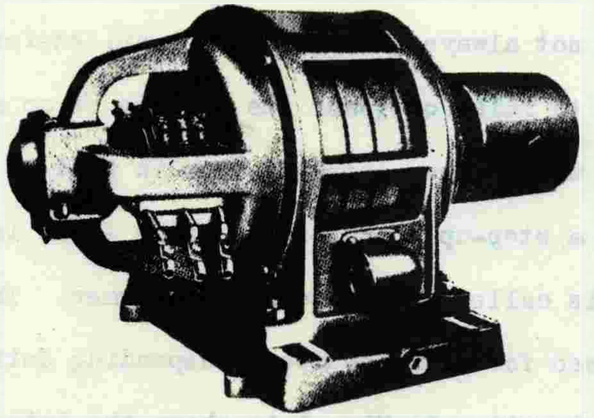

LESSON

64 R

ALTERNATING CURRENT MACHINERY

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ALTERNATING CURRENT MACHINERY

When alternating current power must be transmitted over very long distances, it is most economical to do this at very high voltages so as to reduce the line losses to a minimum. Also, at the consumer's end of an A.C. power line the voltage is not always at a value best suited for the operations it is intended. In order to raise or lower the voltage of an alternating current, transformers are used. When a transformer is used to raise the voltage, it is referred to as a step-up transformer; while if it is used for decreasing the voltage, it is called a step-down transformer. The same transformer, however, can be used for either purpose, depending entirely upon how it is connected into the circuit. In Fig. 1 is shown the interior construction of a modern transformer.

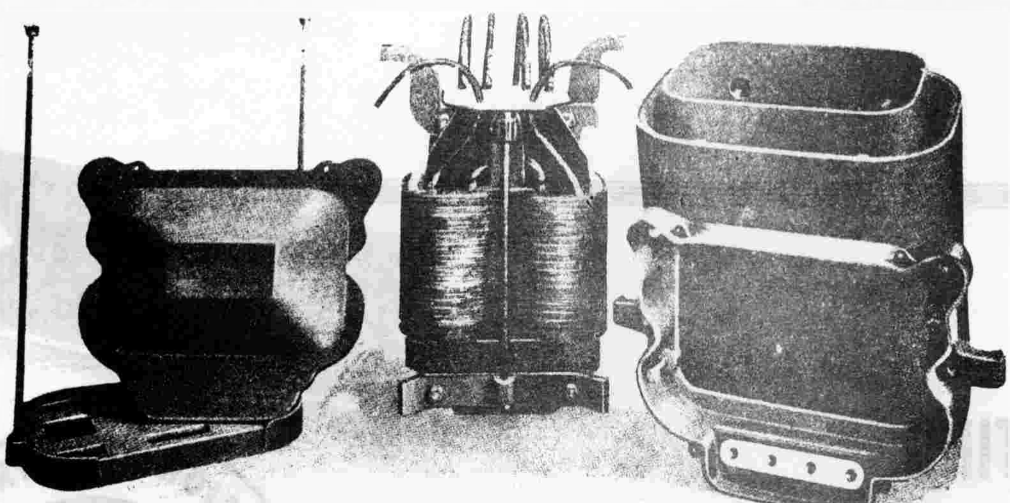

FIG. 1

CONSTRUCTION AND ACTION OF A TRANSFORMER

A transformer as used in commercial practice today consists essentially of three parts, a laminated iron core and two sets of coil windings, one known as the high voltage (high-tension) and the other as the low voltage winding. In larger transformers these parts are mounted in an iron tank filled with special transformer oil, the oil serving as an insulating medium around the coils and windings.

If the transformer is to be used for step-up purposes, the low-voltage winding is used as the primary and is connected to the power circuit, while the high voltage becomes the secondary and delivers the high voltage power to transmission-line or other device in which it is to be used. The operation of the transformer is based upon the principles of electromagnetic induction. When an alternating current is sent through the primary winding, it sets up a magnetic flux within the core. The magnetic flux is a pulsating one and alternately expands and collapses as the current in the winding increases from zero to maximum and then decreases to zero again. As the flux expands and collapses, it cuts the turns of the secondary and induces in them an alternating voltage of the same nature and frequency as was initially impressed across the primary. A transformer merely changes the voltage of an alternating current, but in no way affects the frequency or general nature of the circuit.

Since a transformer depends for its operation upon a pulsating magnetic flux set up in the iron core, and since such a flux can be established only by means of an alternating current, a transformer is purely an alternating current machine and cannot be used on direct current circuits.

TRANSFORMER RATIO

Transformers can be built to cause practically any desired voltage increase or decrease; that is, have any desired transformation ratio. This ratio of transformation depends upon the relative number of turns in the high-tension and low-tension windings. For example, in a small transformer there are 400 turns in the high winding and 100 in the low winding, and the transformation ratio is 4 to 1. If 120 volts are impressed across the low winding, the voltage in the high winding will be four times as great (the same ratio as the number of turns) or 480 volts. On the other hand, if 120 volts are impressed across the high winding, the transformer will step the voltage down to 30 volts. The voltage in the two windings of a transformer are always in the same ratio as the number of turns in the two windings.

TRANSFORMER CONNECTIONS

When the voltage of a single-phase alternating current circuit is to be raised or lowered, a single transformer with a high and low winding is used. In Fig. 2 is illustrated a transformer connected into a single-phase system and is used for step down purposes. The ratio of transformation is 10 to 1; that is, there are ten times as many turns in the high as in the low winding. The primary or impressed voltage is 2300 volts, and the output or secondary pressure is 230 volts

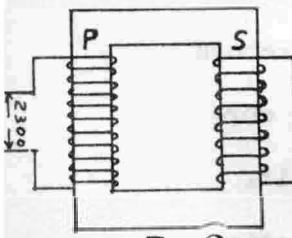

Fig 2

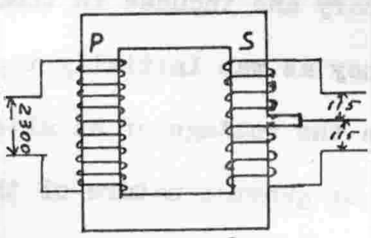

Fig 3

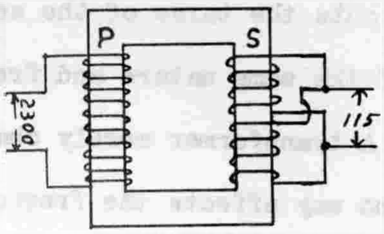

Fig 4

With practically all single-phase transformers it is common practice to have the low winding in the form of two coils with the four leads brought out. If the two coils are connected in series with a tap broughtout from this center connection, as is shown in Fig. 3, two voltages can be obtained from the secondary. The system is thus known as a 3-wire system, and by connecting across the two outer wires a pressure of 230 volts is obtained while by connecting across either outer wire and the middle wire a pressure of 115 volts is obtained. This is very common practice, for the 230 volt pressure is then used for power purposes and motor operation, while the 115-volt pressure is used for lighting purposes. If the two coils are connected in parallel as is shown in Fig. 4, a secondary pressure of only 115 volts is obtained, but the current capacity of the line wires is doubled.

TRANSFORMERS ON THREE-PHASE SYSTEMS

For raising or lowering the voltage of a three-phase system, either a 3-phase transformer can be used or three single-phase transformers. However, 3-phase transformers are very seldom used; it is more common practice to employ three single-phase transformers, for in case of trouble it is much easier to replace one single-phase transformer than to replace a much larger three-phase transformer. In the one case, the system could be operated for a short time on two transformers until the third one was replaced, but in the other case the entire system would be thrown out of commission until the one large transformer was replaced.

When three single-phase transformers are used for voltage transformation on a 3-phase system, a number of different connection arrangements can be used. Both primaries and secondaries can be connected in either star or in delta, or one side can be connected in star and the other in delta. In this manner a large number of different voltage ratios can be secured.

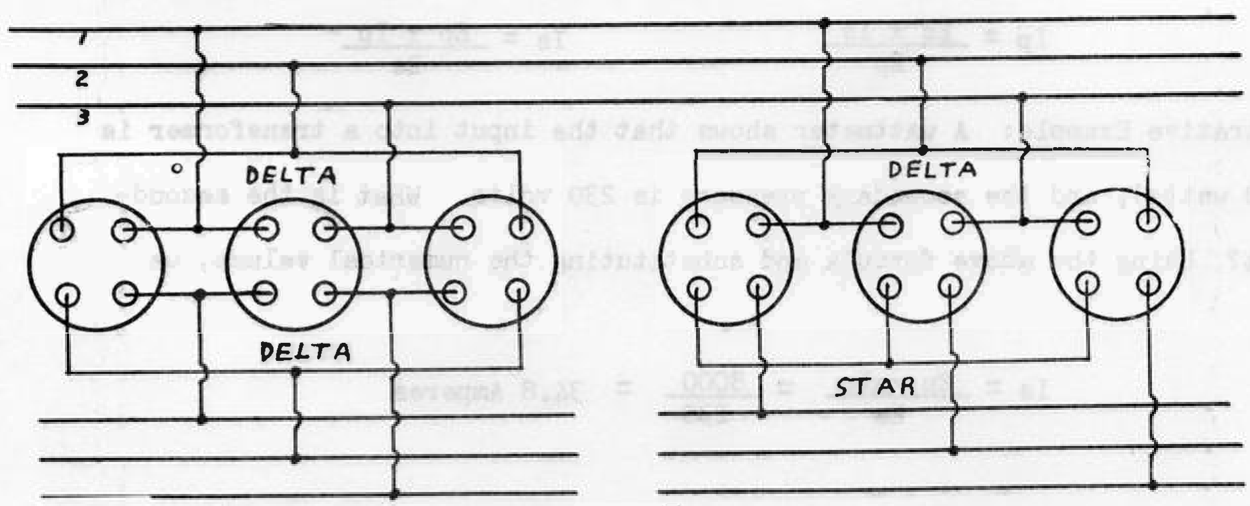

Fig. 5

In Fig. 5, two common methods of connecting three single-phase transformers into a 3-phase system are shown. The set on the left has both primary and secondary windings in delta. Any desired combination of connections can be made, depending upon the requirements of the installation.

POWER, VOLTAGE AND CURRENT RELATIONS

Since there are no rotating or moving parts in a transformer, it is the most efficient of all electrical machines, as there are no losses due to friction or wind resistance, etc. Well built commercial transformers operate at very high efficiencies, ranging from 97 to 99-1/2 per cent.

In any electrical or mechanical machine, the power output is always equal to the power input minus the friction and other losses; and since these losses are very small in a transformer, for all practical purposes, the primary or power input Pp is equal to secondary or power output Ps. But Pp = Ep x Ip and Ps = Es x Is. Since the power input and output are equal, we get: Ep x I p = Es x Is. This states that the primary current times the primary voltage equals the secondary current times the secondary voltage. From this, we see that as the secondary voltage is lowered, the secondary current is increased; and, as the secondary voltage is raised, the current is lowered. In other words, the voltages and currents are inversely proportional. Two other ways of rewriting the above formula are the following:

$$I_p = \frac{E_s \times I_s}{E_p} \qquad I_s = \frac{E_p \times I_p}{E_s}$$

Illustrative Example: A wattmeter shows that the input into a transformer is 8 Kw. (8000 watts), and the secondary pressure is 230 volts. What is the secondary current? Using the above formula and substituting the numerical values, we get:

$$I_s = \frac{E_p \times I_p}{E_s} = \frac{8000}{230} = 34.8 \text{ Amperes}$$

Another important point to remember in transformer calculations is that the power factor on the input side is practically always equal to the power factor on the output side.

SPECIAL CAUTION

Never connect a transformer to a direct-current circuit, for the resistance of the windings is so low to the passage of a direct current that a very large current would flow; and unless the circuit is suitably protected with a fuse or circuit breaker, a serious burnout may occur at some point.

THE INDUCTION MOTOR

The most common type of alternating current motor used for the average power installation is the induction motor. When the power requirements are below one or two horsepower, single-phase motors are used; but where larger motors are required, three-phase motors are installed. In a few districts only two-phase power is supplied, and in such places two-phase motors would have to be used.

An induction motor consists essentially of two parts, a stator or stationary frame and the rotating drum or rotor. The stator of an induction motor is very similar to the stator of an alternating current generator, in that it consists of a circular iron frame on the inner surface of which is built up a laminated iron ring with crosswise slots, and into these slots are placed the electrical windings. In a three-phase motor three independent windings are used, spaced 120 electrical degrees apart. Each winding is arranged into groups, so that the magnetic field set up by the current flowing through each group of coils acts like the flux from a field pole in a direct current machine. With three independent windings there would be three individual circuits. But instead of bringing out six leads, the inner ends of the three windings are connected together so that only three connecting leads are brought out of the machine, similar to a three-phase alternating current generator.

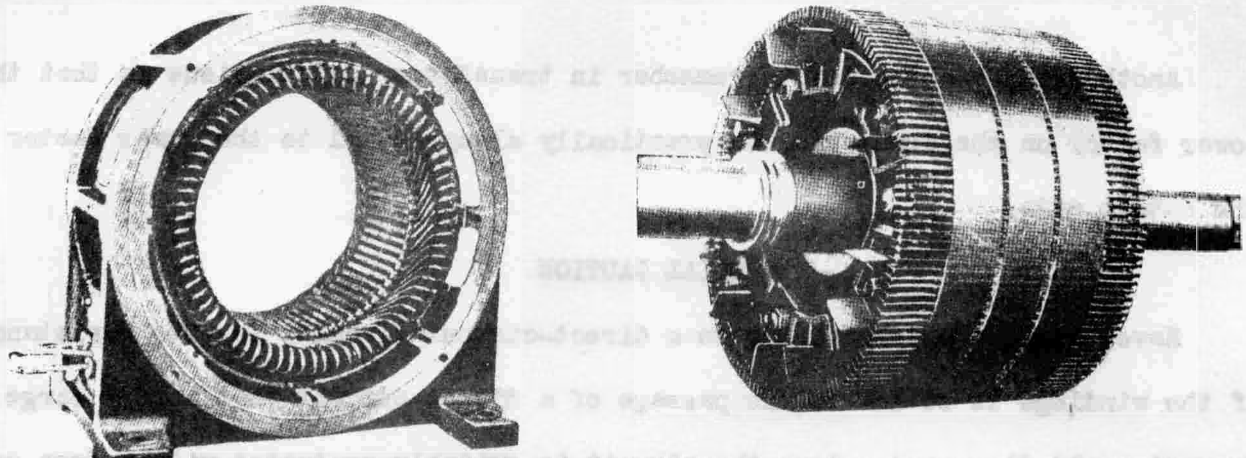

Fig. 6—The stator and rotor of a squirrel cage induction motor.

Two types of rotors are used with three-phase induction motors, and accordingly the motors are classified as squirrel cage motors and wound-rotor motors. The squirrel cage motor is the simplest and most rugged type of motor made. Here the rotor consists of a laminated iron cylinder with parallel slots in the outer surface, and into these slots are placed a series of insulated copper bars. At the ends these bars are welded to a copper ring. The entire winding resembles the familiar squirrel cage, and it is from this that the motor derived its name. Since there are no electrical connections or sliding contacts on the rotor, there is nothing that can easily get out of order and that is why this type of motor is so rugged.

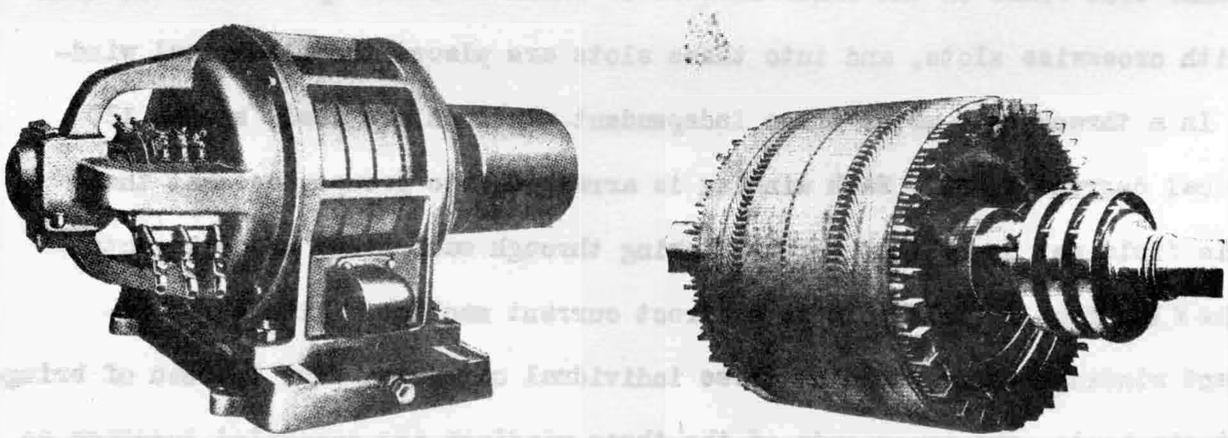

FIG. 7

The rotor and stator of a slip-ring induction motor.

In the wound-rotor type of motor the rotor also consists of a laminated iron cylinder with parallel slots in the outer surface, but into these slots there is placed a regular three-phase winding. The inner ends of the three windings are connected together and the outer ends are connected to a set of three slip rings mounted on but insulated from the rotor shaft. On these rings slide a set of brushes by means of which external connections can be made to the rotor winding. An induction motor having such a wound rotor is sometimes also called a slip-ring motor. The operation of these two types of motors is the same, and they differ only in their starting and variable speed characteristics.

HOW THE INDUCTION MOTOR OPERATES

The principle of operation of the induction motor is similar to that of the direct current motor, namely the force of repulsion existing between the magnetic field set up by the rotor and that set up by the stator. The difference lies only in the manner in which the current is caused to flow in the rotor.

The induction motor employs what is known as a rotating magnetic field. A rotating magnetic field is merely a magnetic flux that moves or shifts around the inner surface of the stator winding. It was previously explained that the stator winding consists of three individual windings with the coils of each arranged into groups so that they set up magnetic fields similar to those set up by the north and south poles of a direct current machine. But since the current flowing through the induction motor windings is alternating, the magnetic field also is variable in nature. Let us assume that the first coil group of winding No. 1 sets up a north pole, and the second coil group would then set up a south pole. But winding No. 2 is advanced 120 electrical degrees; and as the current in winding No. 1 decreases from maximum, the current in No. 2 is approaching maximum. Similarly the field strength of No. 1 is decreasing and of No. 2 is increasing, and within one-third of a cycle the north pole has shifted from winding No. 1 to No. 2. In the same manner winding No. 3 is advanced 120 degrees ahead of No. 2; and as the current in No. 2 decreases from maximum, that in No. 3 is approaching maximum. Consequently within another third of a cycle the north pole has shifted forward 240 degrees or two-thirds of the distance around the machine (in the case of a bi-polar machine). In like manner the south pole has shifted from winding No. 1 to No. 2 in the first third of the cycle, and from No. 2 to No. 3 in the second third of the cycle. In the next third of the cycle the north pole shifts to the second coil group of winding No. 1 where a south pole was initially.

It can be seen that due to the variable nature of the alternating current and the fact that the successive windings are advanced 120 degrees or a third of a cycle, a magnetic field is created that is constantly shifting or rotating along the inner surface of the stator winding. The effect is the same as though a number of field poles like those of a direct current machine were rotating around the inner surface of the stator frame.

The speed of rotation of this magnetic field depends upon the frequency of the alternating current and the number of poles for which the stator winding is wound. If the frequency is 60 cycles per second and a 2-pole winding is used, the speed would be 60 revolutions per second or 3600 revolutions per minute (R.P.M.). If it is a 4-pole machine the speed would be 1800 R.P.M.

In the case of a squirrel-cage motor, as this magnetic field revolves around the inside of the stator, the lines of force cut the bars of the squirrel cage winding and induce in each an electric current. This current flows along the bars and through the end ring to the other side of the winding. In this manner a current is induced in each bar. These currents set up around each bar a magnetic field and the reaction between these fields and the field set up by the current through the stator winding causes the rotor to turn. The operation is really a transformer action, for the current flowing through the stator (primary) winding sets up a movable magnetic field, and this magnetic field in turn induces a current in the rotor (secondary) winding. It is from this inductive action that the induction motor derived its name.

MOTOR SPEED AND SLIP

It is evident that if the rotating magnetic field is to cut the conductors of the cage winding, the field must revolve faster than the rotor turns, for if both turned at the same speed, the lines would not be cut. But since the speed of the magnetic field is determined by the frequency of the alternating current and the number of poles in the stator winding, it will always be constant. Therefore, the rotor will always lag behind the field. The amount by which the rotor lags behind the field of rotation is known as the slip of the motor and is expressed in per cent. If the field speed of a motor is 1800 R.P.M. and the rotor speed is 1675 R.P.M., the amount of slip would be 1800-1675 or 125 R.P.M. Expressed in per cent this would be 125/1800 or 7%. This means that the rotor is turning 7% slower than the field.

The amount of rotor slip depends upon the load which the motor is required to pull. The rotor will always turn at such a speed that the rotating field can induce enough current in the rotor bars to enable the motor to develop the necessary torque. If the load is light, only little rotor current is needed, and the rotor speed will be nearly equal to the field speed. If the load is heavy, the rotor will slow down so as to allow enough current to be induced in the rotor winding to develop the required torque. The motor automatically controls its own speed--as the load increases, it slows down in order that a greater current will be induced in the rotor windings so as to develop a larger torque; and as the load decreases, the motor speeds up until just enough current is induced to produce the necessary torque again.

THE SLIP-RING MOTOR

In a slip-ring or wound-rotor type of induction motor the operation is exactly the same, except that in this case the current induced in the secondary circulates through the entire three-phase winding. The magnetic field around this winding then reacts with the field of the stator winding and the rotor is caused to turn. When in the running condition the rotor windings are shorted onto themselves and the action is the same as with the squirrel-cage winding.

The slip-ring motor also controls its own speed automatically, the speed decreases as the load comes on and increases as the load is taken off. The advantage of the slip-ring motor lies in the fact that its starting characteristics can be controlled when the motor is under load. Also the speed can be controlled within certain limits.

STARTING INDUCTION MOTORS

Various types of starting devices are used for starting induction motors, depending upon the size of the motor and the type of service for which it is to be used. Small single-phase motors are generally thrown directly across the line, although if the motor is under load the line voltage may be affected quite seriously due to the heavy starting current.

Small three-phase motors of the squirrel-cage type are also started by being thrown directly across the line, but a special 3-pole double-throw switch is used for this purpose. When the switch is thrown into the starting position, the line fuses are out of the circuit; but when the motor has come up to speed and the switch is thrown into the running position, the fuses are in series with the line feeding the motor. The reason for this practice is that the fuses are to protect the motor against overload, but the starting current is so large that the fuses would be blown instantly. Therefore, during the starting period the fuses are cut out of the line and cut in again after the motor has come up to normal speed.

Larger squirrel cage motors are generally started by means of a "starting compensator." This also consists of a double-throw switch which when thrown into the starting position cuts into the line three auto transformers which reduce the voltage supplied to the motor. When the motor has come up to speed, the lever is thrown into the running position and full line voltage is supplied to the motor.

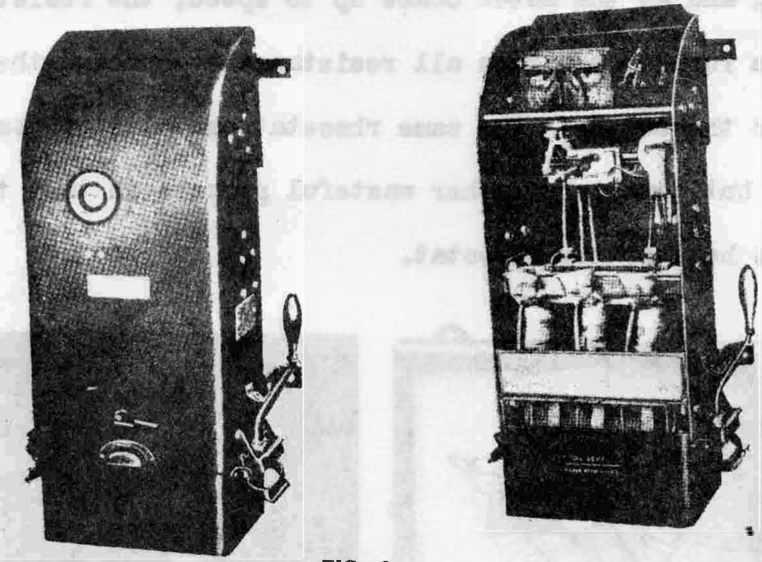

FIG. 8

When the compensator is in the running position, overload relays are in series with the line. These relays are merely electromagnets with a movable plunger; and when the current exceeds a certain value, the plunger is drawn up and the circuit is opened. The entire starting operation must then be repeated to put the motor back into operation. These starting compensators are used both in the manually (hand) operated type and the automatic type operated by means of push-buttons.

Another starting device that is used with squirrel-cage motors up to 15 horse-power is the star-delta starting switch. This again is a double-throw switch. When the switch is thrown into the starting position the three stator windings are connected in "star" and as a result only 58% of the full line voltage is supplied to the motor. When the motor has come up to speed, the switch is thrown into the running position, and the three windings are connected in "delta," full line voltage then being applied to the motor windings.

The common method of starting wound-rotor or slip-ring induction motors is by means of a starting resistor connected into the rotor windings. This rheostat, as is illustrated in Fig. 9 on page 13 consists of three variable resistors, one connected into each of the three rotor windings and all three operated by means of a single hand lever. When the motor is to be started, all resistance is cut into the rheostat, and as the motor comes up to speed, the resistance is gradually cut out. In the running position all resistance is out and the three windings are shorted onto themselves. The same rheostat can also be used as a speed control device, but this is a rather wasteful process in that the excess energy is dissipated as heat in the rheostat.

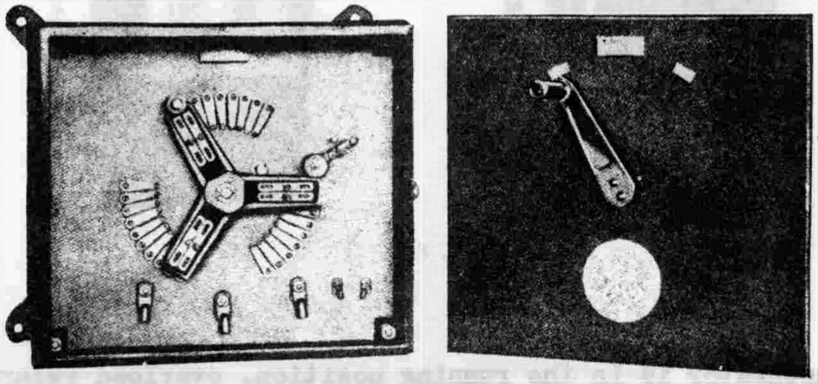

FIG. 9

Hand-operated three-phase resistor for starting slip-ring induction motor.