POLYPHASE GENERATORS, MOTORS AND MOTOR-GENERATORS

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STUDY SCHEDULE NO. 28

For each study step, read the assigned pages first at your usual speed. Reread slowly one or more times. Finish with one quick reading to fix the important facts firmly in your mind, then answer the Lesson Questions for that step. Study each other step in this same way.

☐ 1. Elementary Polyphase Generators . . . . Pages 1-4

Elementary two-phase and three-phase generators are discussed in this section. Answer Lesson Question 1.

☐ 2. Delta and Y Connections . . . . Pages 4-8

You study two methods for connecting an alternator to a three phase load with only three wires. Answer Lesson Questions 2, 3, 4, and 5.

☐ 3. Commercial Alternators . . . . Pages 8-13

The rotating-armature type, the rotating-field type, factors affecting voltages, and factors affecting frequency are described here.

☐ 4. Three-Phase A.C. Motors; Three-Phase Synchronous Motors; Three-Phase Induction Motors . . . . Pages 13-22

In this section you learn the characteristics of these different types. Answer Lesson Questions 6, 7, 8, and 9.

☐ 5. Motor Generator Sets; Dynamotors and Rotary Converters . . . . Pages 23-26

Here you study these two special machines designed to develop low power, single-phase currents from d.c. power, or the reverse.

☐ 6. Maintenance of Motors and Generators . . . . Pages 26-28

A few of the most common maintenance problems are discussed in this section. Answer Lesson Question 10.

☐ 7. Answer Lesson Questions.

☐ 8. Start Studying the Next Lesson.

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Polyphase Generators, Motors and Motor-Generators

Elementary Polyphase Generators

A POLYPHASE alternator* is essentially a combination of two or more single-phase generators constructed as a single unit with the output voltages having a definite phase relationship to each other, so let us review briefly at this time the principles underlying an elementary single-phase alternator like that shown in Fig. *1A*. This alternator consists of a single-turn loop *1* rotating in the fixed magnetic field set up by a two-pole electromagnet which is excited by direct current in such a way as to produce the indicated polarity at the poles. The voltage generated in the single loop is led out to the external circuit by means of brushes B_1 and B_2, contacting slip rings S_1 and S_2 which are connected to the two ends of the loop. Curve E_1 in Fig. *1B* shows the variations in the magnitude and polarity of the voltage induced in the loop of wire as it rotates in the magnetic field in the direction shown.

When the loop is in the position shown in Fig. *1A*, the induced voltage is zero. As the loop is rotated in the clockwise direction indicated, brush B_1 is positive with respect to B_2 during the first half-revolution (first half-cycle), negative with respect to B_2 during the next half-revolution, etc. (Curve E_1 in Fig. *1B* gives the polarity of brush B_1 with respect to brush B_2.) Since a two-pole d.c. field structure is employed, the induced voltage goes through a complete cycle of variation for each revolution of the armature loop. This means that if the armature loop rotates 60 times per second (3,600 r.p.m.), one revolution takes 1/60 of a second, and a complete cycle of voltage values occurs in this time (1/60 second). Curve E_1 in Fig. *1B* can therefore be made to represent the magnitude and polarity of the induced voltage plotted against time.

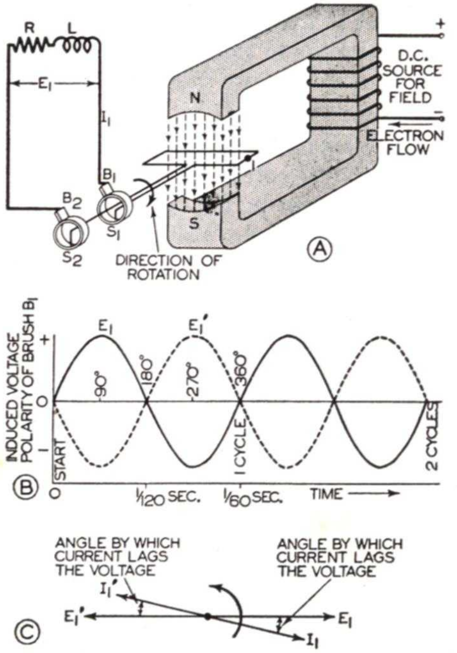

FIG. 1. Elementary single-phase a.c. generator connected to an inductive load, with current and voltage relationships for this condition.

***"Poly" is the Greek word for "many," hence "polyphase" means "many phases." The terms "a.c. generator" and "alternator" are interchangeable in electrical engineering terminology.**

Now suppose that a load comprising a resistance R and an inductance L in series is connected to the brushes. The electron flow I_1 through this load will lag the generator output voltage E_1 by a phase angle which depends upon the relative magnitudes of the resistance and the inductive reactance in the load. (In our study of elementary one-, two- and three-phase generators, we will for simplicity assume that the generator windings have no impedance. Under this assumption, the induced voltage for a winding or phase is the same as the terminal voltage for that phase regardless of the nature of the load.) Instead of drawing a curve for I_1 similar to that for E_1, it is more convenient to use a vector diagram like than in Fig. *1C*.*

Reversing the Direction of Rotation. When the direction of rotation of the armature loop in Fig. *1A* is reversed, the direction of the induced voltage in the loop will be reversed, and therefore the polarity of the brushes will be reversed. Curve E_1' in Fig. *1B* represents the induced voltage and the polarity of brush B_1 with respect to B_2 under these conditions, and vector E_1' represents this same voltage in Fig. *1C*. The load current at any instant will lag the generated voltage by the same angle as before, so the new current vector will be I_1'. The vector diagram shows clearly that both the voltage and current are shifted by 180° (are reversed in phase) when the direction of rotation is reversed. Obviously, the same result could have been obtained (insofar as the load is concerned) by reversing the load connections to the brushes.

Elementary Two-Phase Generator

Now let us add one extra loop to the elementary generator in Fig. *1A*, placing it at right angles to the first loop as shown in Fig. *2A* and connecting it to an extra pair of brushes and slip rings. As the coils are rotated, each loop will generate one complete cycle of a sine wave voltage for each revolution. When the loops are in the positions shown in Fig. *2A*, the voltage induced in loop *1* will be zero (the flux through the loop is not changing) and the voltage induced in loop *2* will be a maximum (the flux through the loop is changing at a maximum rate). Curve E_1 in Fig. *2B* represents the voltage induced in loop *1* and the polarity of brush B_1, and curve E_2 represents the voltage induced in loop *2* and the polarity of brush B_3.

Careful study of Fig. *2B* will show that voltage E_2 (induced in loop *2*) reaches its maximum positive value, its zero value, its maximum negative value, etc., one-fourth of a cycle *ahead* of loop *1*. Since one-fourth cycle is 90°, we can say that voltage E_2 *leads* E_1 by 90°, or E_1 *lags* E_2 by 90°. This is shown also by the vector diagram in Fig. *2C*, where E_2 is ahead of (leads) E_1 by 90° as the vectors rotate in a counter-clockwise direction.

Each of the independent circuits in the elementary generator of Fig. *2A* is referred to as a *phase*, and the machine is known as a *two-phase alternator*. The two generated voltages in a *two-phase alternator* are always 90° out of phase with each other.

***Vector diagrams have been taken up from time to time in your course as the need for them arose. Furthermore, you have been given a complete presentation of the entire subject of vector diagrams elsewhere in the course. If you have any difficulty whatsoever in interpreting the vector diagrams in this lesson, look up these vector discussions and review them carefully.**

Assume now that identical loads made up of R and L are connected to each of the two phases in Fig. *2A*. The current in each phase will then *lag* the phase voltage by an angle depending upon the relative magnitudes of the resistance and the inductive reactance. This is shown in Fig. *2C* by the positions of the current vectors I_1 and I_2. If the lag angles in the two circuits are identical (as is the case for identical loads), the currents in the two phases will be exactly 90° out of phase with each other.

Elementary Three-Phase Generator*

Now assume that there are three equally spaced loops on an elementary generator, with a pair of slip rings and a pair of brushes for each loop or phase, as indicated in Fig. *3A*. As the armature revolves in the direction shown, the voltages induced in each loop from instant to instant will be as shown by curves E_1, E_2 and E_3 in Fig. *3B*. The voltage in phase *1* leads the voltage in phase *2* by 120°, and the voltage in phase *2* leads the voltage in phase *3* by 120°. This machine is called a three-phase alternator, and provides voltages which are *120 degrees out of phase with each other.*

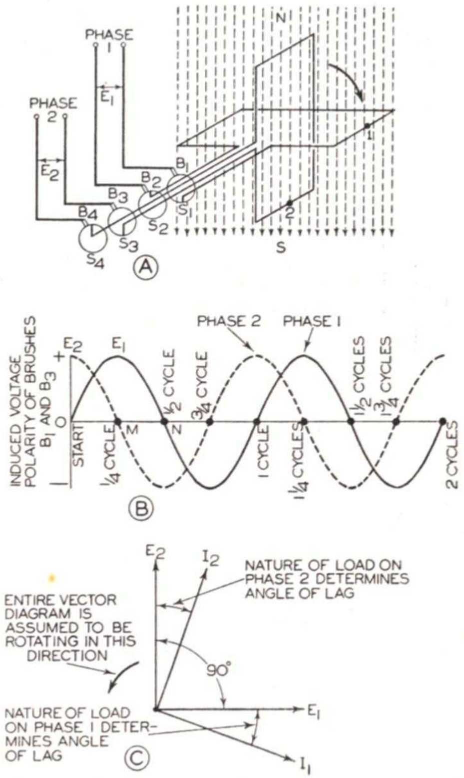

FIG. 2. Elementary two-phase a.c. generator, and relationships of currents and voltages in it when identical inductive loads are connected to each phase.

The vector diagram for an elementary three-phase alternator is shown in Fig. *3C*. If identical loads (comprising R and L in series) are connected to each of the three phases, the currents I_1, I_2 and I_3 will be equal in magnitude and will lag their respective voltages by an identical phase angle. The current vectors will be 120° out of phase with each other in this case.

When each phase of an elementary three-phase generator has exactly the same size and type of load, the gener-

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***The usual procedure employed in teaching the subject of three-phase dynamo-electric machinery to radio men is simply to present the important facts without explaining their meanings or why they are true. We go into the subject more deeply in this book and give you reasons for each statement wherever possible, for we want you to be better informed than the average radio man. It is to be expected, therefore, that mastery of this lesson will not be easy, nor can it be accomplished in one or two readings.**

Do not spend too much time and effort *now* on this lesson. Read it through carefully once, then study it section by section until you are able to answer the questions. After that proceed with the next lesson, but plan on reviewing this lesson at least twice before completing your course. Remember—this is one of the most difficult lessons in the Communications Course; other lessons will be considerably easier.

ator is said to be *balanced.* When the loads are such that the currents are unequal in magnitude or make different phase angles with their respective applied voltages, the generator is said to be *unbalanced.*

Delta and Y Connections

The elementary three-phase alternator of Fig. *3A* has one pair of slip rings and one pair of brushes for each of its three phases. In practice, this would represent a wasteful use of copper since six wires would be required to transfer the generated power to loads requiring three-phase a.c. for their operation. To eliminate such waste, engineers have devised two different methods for connecting an alternator to a three-phase load *with only three wires.* The connections are made within the armature, so that only three slip rings and three brushes are required. The connections are referred to as the *delta* (or *mesh*) and the *Y* (or *star*) connections.

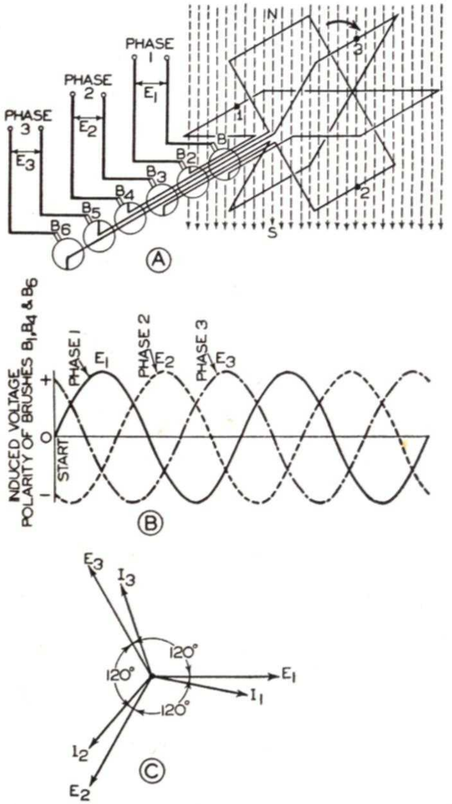

FIG. 3. Elementary three-phase a.c. generator, and relationships of voltages and currents in it when identical inductive loads are connected to each phase.

Delta Connection. The delta connection for a three-phase alternator is shown in Fig. *4A.* (The name *delta* is derived from the resemblance of this diagram to the Greek letter *Δ*, which is called delta. (The actual connections on the armature bear no resemblance to a delta.) The three windings are connected to three common connecting points *a, b* and *c,* and these points are in turn connected to the output terminals of the machine through three brushes sliding over three slip rings on the armature shaft. The voltages induced in the phase windings are indicated as E_{1-2}, E_{3-4} and E_{5-6} respectively, and are commonly referred to as *phase voltages.* The three output voltages of the machine exist between pairs of terminals, and are indicated in Fig. *4A* as E_A, E_B and E_C.

To get a delta connection for a three-phase alternator, the phase windings must be connected together *all in series in such a way that the voltages around the resulting closed circuit add up to zero.* If an appreciable resultant voltage existed, it would send a large circulating current around the delta circuit, causing heavy circuit losses in the alternator.

A consideration of the vector diagram for this arrangement will show that the resultant voltage acting on the closed armature circuit of a delta-wound three-phase generator *is zero* As shown in Fig. *4B,* the phase voltage vectors E_{1-2}, E_{3-4} and E_{5-6} are all 120° out of phase with each other and are equal in magnitude. Let us combine any two of these vectors, such as E_{3-4} and E_{5-6}; we get vector E_{3-6} as the resultant of the two, and can readily see that it has the same magnitude as the other three vectors. Now combine E_{3-6} with the remaining original vector E_{1-2}; since the two are equal and 180° out of phase, the result is zero. This means that the resultant voltage acting on the closed delta circuit is zero, and theoretically there will be no circulating current in this circuit. (Actually a small current always circulates around this path and produces small losses, for the voltages of the phases in a practical alternator are never exactly equal even with balanced loads.)

In any discussion of a.c. circuits or a.c. machinery, the two important facts about an a.c. voltage are its *magnitude* (peak or r.m.s.) and its *phase with respect to other voltages or to currents in the circuit.* A vector diagram gives this information for each voltage; for example, Fig. *4B* tells us that when E_{1-2} is zero, E_{3-4} is approaching its maximum negative value, and will be zero after 120 electrical degrees of rotation. (Vectors above the horizontal reference line represent positive values of voltage, and vectors below this line represent negative values of voltage.)

The order of the numerals in the voltage notations has a particular significance which is best explained by means of examples. E_{3-4} means that we are considering the potential of terminal *3* with respect to terminal *4;* the vector diagram indicates that this potential is negative, and hence terminal *3* is negative with respect to terminal *4* for the instant of time represented by the vector diagram in Fig. *4B.* Likewise, Figs. *4A* and *4B* together tell that at this instant of time, voltage E_{5-6} makes terminal *5* positive with respect to terminal *6.*

Now let us see what relationships exist between the induced (phase) voltages and the output voltages in a delta-connected three-phase alternator. The circuit diagram in Fig. *4A* shows that output voltage E_A is produced by phase *A* acting in parallel with the series combination of phases *B* and *C.* The voltage due to phases *B* and *C* in series is obviously the vec-

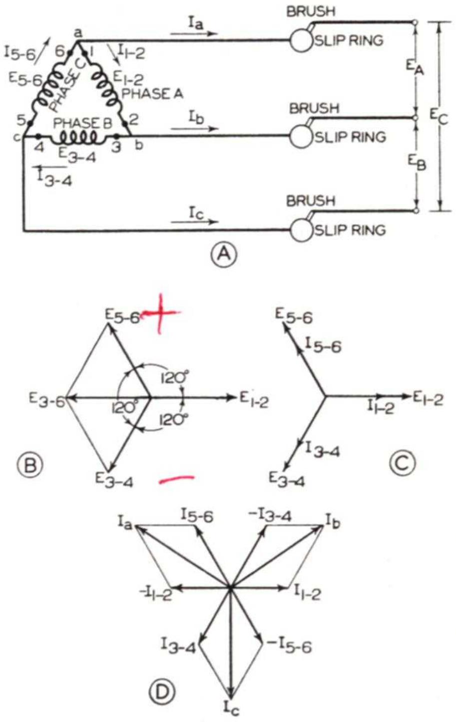

FIG. 4. Delta or mesh connection for a three-phase alternator, with voltage and current vector diagrams for a balanced load condition. Vectors rotate counterclockwise.

torial sum of E_{5-6} and E_{3-4}; adding these on the vector diagram gives E_{3-6} as the voltage acting in parallel with E_{1-2}. Note, however, that E_{3-6} represents the potential of terminal *3* (and *b*), whereas E_{1-2} represents the potential of terminal *1* (and *a*); we must therefore reverse vector E_{3-6} so it represents the potential of terminal *6* (and *a*). This reversal makes it E_{6-3}, and places it right on top of E_{1-2} since E_{3-6} is equal in magnitude to E_{1-2}. The two parallel voltages which make up E_A are therefore equal and in phase. Since parallel voltages do not add, the line voltage E_A is equal in magnitude to the phase voltage E_{1-2}. By similar analysis it can be shown that the three line voltages (E_A, E_B and E_C) and the three phase voltages (E_{1-2}, E_{3-4} and E_{5-6}) all have the same magnitude. Furthermore, under no-load or balanced load conditions, E_A, E_B and E_C are 120° out of phase with each other, with E_A leading E_B and E_B leading E_C.

Electrical engineers employ a simple and rather unique method for studying the currents in complicated a.c. circuits. They simply assign a direction arbitrarily to the current flowing through each part at any one instant, then proceed to figure out the magnitudes and phases of these currents. If a current value has a minus sign in the final result, the engineers know that this current flows in the opposite direction to that originally assumed for that instant. They can either deal with current flow or electron flow, as they prefer. Electrical engineers almost always deal with current flow, and consequently the directions indicated for currents in books on motors and generators will be the opposite of those for electron flow. (Keep this in mind when studying electrical books or magazines.) Let us employ this technique for studying the currents in our delta-wound three-phase generator.

First of all, we assign directions to the phase currents I_{1-2}, I_{3-4} and I_{5-6} and to the line currents I_A, I_B and I_C, as indicated by the arrows in Fig. *4A*. We can say that these arrows indicate the direction of electron flow or current flow, as we prefer, provided we stick to our selected interpretation throughout the analysis. Next, assume that the three phases of our generator are uniformly loaded, and in such a way that the voltage and current for each phase (such as E_{1-2} and I_{1-2}) are *in phase* with each other. The phase currents will therefore be 120° out of phase with each other, as indicated on the vector diagram in Fig. *4C*.

From Fig. *4A* it will be apparent (giving due regard to the assumed directions for current flow) that $I_a = I_{5-6} - I_{1-2}$. Similarly, $I_b = I_{1-2} - I_{3-4}$, and $I_c = I_{3-4} - I_{5-6}$. Figure *4D* shows the constructions required to subtract these phase currents on a vector diagram and secure the line currents. By measuring the resulting line current vectors I_a, I_b and I_c with a ruler and comparing their lengths to the lengths of the phase current vectors, you will find that the line currents for a balanced three-phase delta-wound generator are 1.73 times the magnitudes of the phase currents. Furthermore, the line currents under this condition are 120° out of phase *with each other*. This vector diagram also indicates that I_c is negative, which means that for the instant of time being considered, this current will flow in the opposite direction to that assumed in Fig. *4A*.

Summarizing for the delta-wound three-phase alternator with balanced loads, the line voltages and line currents form balanced vector systems, as do the phase voltages and phase currents. The line voltages *are equal to the phase voltages* induced in the armature. Each line current *is equal to 1.73 times the armature current per phase.*

If the load currents are unequal, or not 120° apart in phase, the line currents will be unequal and so will the phase currents. Armature reaction will then be unequal, with the result that the induced voltages in the three windings (the phase voltages) will be unequal. As a result, the sum of the three phase voltages will not add up to zero and a circulating current will exist. This circulating current adds to the I^2R losses of the machine without serving a useful purpose.

Y Connection. When the armature windings of a three-phase alternator are connected together in the manner shown in Fig. *5A*, we have what is known as a Y or star connection. (The resemblance of this diagram to the letter Y or to a star is obvious.) One end of each winding is connected together at *o*, and the other ends of the windings are connected to the three slip rings. Connections are such that the phase voltages E_{1-2}, E_{3-4} and E_{5-6} form a balanced three-phase system, as shown in Fig. *5B*.

Reference to Fig. *5A* shows that line voltage E_X is furnished by phase windings *A* and *B* in series. E_X is therefore equal to the vectorial sum of phase voltages E_{1-2} and E_{3-4}. E_{3-4} is acting in the opposite direction to E_{1-2} along path *a-o-b*, however, so we must reverse vector E_{3-4} (rotate it 180°) before adding. This gives vector $-E_{3-4}$ in Fig. *5B*, and adding this to E_{1-2} gives vector E_X as one of the line voltages. By measuring its length, we find that it is 1.73 times the magnitude of a phase voltage. Similarly, $-E_{5-6}$ is added to E_{3-4} to get line voltage E_Y, and $-E_{1-2}$ is added to E_{5-6} to get line voltage E_Z. Note that the three line voltages (E_X, E_Y and E_Z) are equal to each other and are 120° apart in phase.

The circuit diagram in Fig. *5A* shows that the line currents, I_a, I_b and I_c, are identical with the corresponding phase currents, I_{1-2}, I_{3-4} and I_{5-6}. This is shown vectorially in Fig. *5C*.

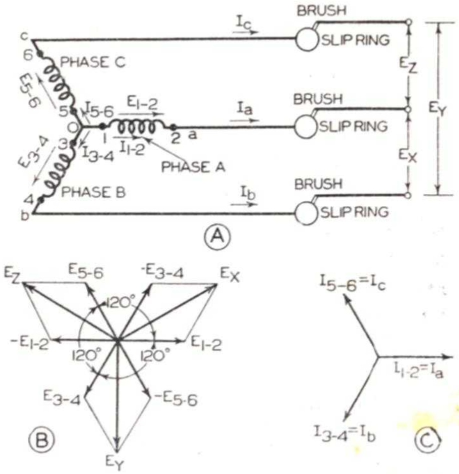

FIG. 5. Star or Y connection for a three-phase alternator, with voltage and current vector diagrams for a balanced load condition.

Summarizing for the Y connection with balanced loads, the line voltages and line currents form balanced vector systems, as do the phase voltages and phase currents. The line voltages *are equal to 1.73 times the phase voltages.* The line currents *are equal to the phase currents.* Remembering that with a delta connection the line volt-

ages are equal to the phase *voltages*, you can readily see that *a Y connection of the phase windings gives higher line voltages than a delta connection*.

It is of interest to note that the common connection of the three phase windings, point *o* in Fig. *5A*, may be brought out to a fourth slip ring. A balanced system of voltages equal to the phase voltages would then be available betwen this extra slip ring and the other three slip rings. This connection to the common terminal of the windings is called a *neutral connection*, and is sometimes used when two sets of three-phase voltages, each of a different magnitude, are required. Under balanced load conditions, the neutral wire carries no current, for the three equal currents in it are 120° apart in phase and add up to zero when combined vectorially. When a neutral wire is used, it is usually grounded, for neutral point *o* in Fig. *5A* is generally connected to the grounded frame of the generator.

Commercial Alternators

The three-phase alternator is the most important of all a.c. generators. A single-phase voltage may be obtained from it by connecting to any two of the three terminals. A two-phase voltage may be obtained from it by the use of a special transformer connection (called the Scott transformer), which we shall not discuss here because of its limited application. A six-phase voltage may be obtained from it by a simple transformer connection which splits each voltage into two equal 180°-out-of-phase voltages and thereby gives six voltages 60° apart in phase. Commercial generation of power is, therefore, limited to three-phase machines, either of the rotating-armature type or the rotating-field type.*

Rotating - Armature Type. Low-voltage three-phase alternators with low power ratings invariably employ a rotating armature. Each phase of the alternating current winding on the armature is like that of a d.c. generator without a commutator, and can be either a lap winding like that in Fig. *6A* or a wave winding as in Fig. *6B*. The a.c. line connections are brought out through slip rings and brushes. The magnetic field system is the same as for a d.c. generator, except that the field must be excited from a separate source (no d.c. is provided by the armature). The limitations as to voltage and power capacity arise from the difficulty of insulating the slip rings and brushes for high voltage and the difficulty of handling heavy currents with brushes.

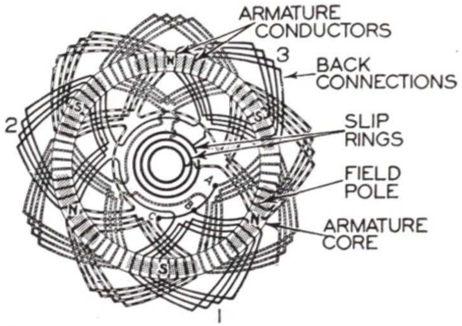

FIG. 6A. Winding diagram for a lap-wound, Y-connected rotating armature of a small three-phase alternator. The stationary field structure has six poles. For simplicity, the armature core is flattened out in the plane of the paper so that the armature conductors are drawn radially. All front connections (at the slip ring end) are therefore shown inside the armature core. and back connections are shown outside the core ring. Each phase winding is represented by a different type of line to simplify tracing of circuits. One end of each phase winding is connected to the common connection (*A-B-C*), and the other end of each winding is connected to a slip ring. Any one phase winding, such as that shown in solid black lines, has three sets of winding elements (*1*, *2* and *3*) in series, with opposite sides of each winding element separated by one-sixth of the armature circumference so they come under the influence of opposite d.c. field poles.

Rotating - Field Type. Alternators with rotating d.c. fields are invariably used in radio work whenever a large amount of three-phase a.c. power is to be generated. These units have a stationary armature which is directly connected to the three-phase load. The d.c. magnetic field structure rotates inside this stationary armature, and is connected through a pair of slip rings and brushes to a low-voltage, low-power d.c. field supply.

Factors Affecting Voltage. Whether the alternator is of the rotating-armature or the rotating-field type, the voltage induced in each phase winding is proportional to the number of winding elements (loops) in series in the armature winding, to the strength of the magnetic field (per pole), to the number of pairs of field poles, and to the speed of the rotor. (The rotor is the part which rotates; it can be either the a.c. armature structure or the d.c. field structure.) The induced voltage, therefore, depends upon the *rate of change of flux linkages*.

Factors Affecting Frequency. The frequency of an alternator is proportional to the number of d.c. poles and to the speed of the rotor, and is determined according to the following formula, which holds true regardless of the number of phases:

$$f = \frac{P \times n}{120}$$

In this formula, f is the frequency in cycles per second, P is the number of poles in the d.c. field, and n is the speed in r.p.m.

Example: For a sixteen-pole machine revolving at 450 r.p.m., the frequency in cycles per second is: $f = 16 \times 450 \div 120 = 60$ cycles per second.

The standard frequency in the United States is 60 cycles per second, but alternators are made for many other frequencies to meet special requirements. A 60-cycle alternator designed to be driven by low-speed driving units such as a steam engine, oil (Diesel) engine, or large water turbine must have a large number of poles (oftentimes as many as thirty-two) if it is to be directly connected to the driving unit. Alternators directly connected to a high-speed steam turbines or to gasoline engines require only four to six poles.

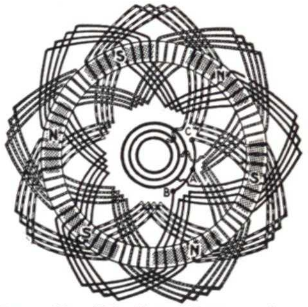

FIG. 6B. Winding diagram for a wave-wound, Y-connected rotating armature of a small three-phase alternator having stationary field poles.

Typical Commercial Three-Phase Alternator. Figure *7A* shows a typical slow-speed rotating-field type three-phase alternator. The stationary armature consists of a laminated steel core having slots in which the armature conductors are placed. The individual laminations are coated with a varnish which insulates them from each other and thereby prevents wasteful eddy currents in the core.

The coils of the stationary armature

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*The armature in an a.c. generator is that part which feeds power into the line. If the armature is stationary, it is directly connected to the line; if rotating, the connection is made through slip rings and brushes.

are formed and insulated before being placed in the armature slots and connected together to give either a wave or lap type winding. The wave winding allows more winding elements per pole per phase, and hence is more useful for high-voltage machines up to 2,200 volts per phase. The lap winding provides for the use of multiple paths per phase and is thus applicable to high-current, low-voltage service.

The revolving twenty-eight-pole d.c. field structure of this alternator is shown in Fig. *7B*. The field poles consist of laminated sheet steel plates riveted together and either bolted or dovetailed to the rotor spider. The field coils are wound around the field poles and are connected so as to form alternate north and south poles. A small d.c. generator (125 volts) directly coupled or geared to the main shaft is used to supply a d.c. voltage to the brushes on the two slip rings for field excitation purposes.

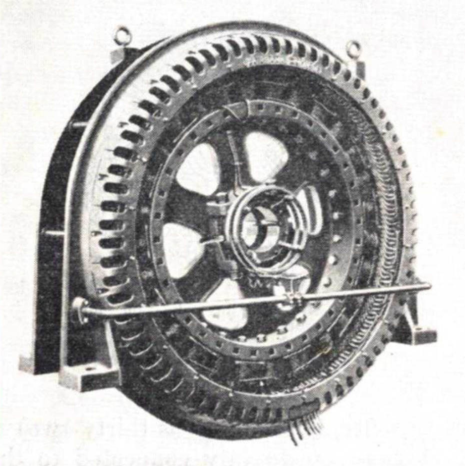
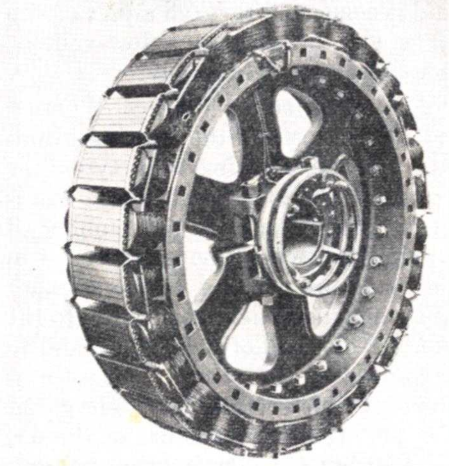


FIG. 7A. This Fairbanks-Morse slow-speed three-phase generator is typical of large power-generating units employing a rotating d.c. field structure and a stationary armature.



Courtesy Fairbanks-Morse and Co.

FIG. 7B. Rotating d.c. field structure of the alternator at the left. This unit produces 60-cycle power when driven at rated speed of approximately 257 r.p.m.

Note the copper bars embedded in the faces of the field poles in Fig. *7B*. These bars are connected together to form short-circuited coils similar to the rotor of an induction motor, and serve to maintain a constant output frequency even though the prime mover is somewhat irregular in its speed characteristics. Slight variations in speed produce a relative motion of the short-circuited windings with respect to the field produced by armature reaction. The resultant induced currents produce torques which tend to prevent the changes in speed.

Operating Characteristics of Three-Phase Alternators. As you know, the term *voltage regulation* is used as a figure-of-merit of any generator, a.c. or d.c. It refers to the per cent change in voltage between no-load and full-load conditions, *expressed in terms of the full-load voltage*. For a three-phase alternator, the line voltage between any two wires is used. For example, if the line voltage is 2,200 volts when a full-load line current of 50 amperes is delivered, and the voltage rises to 2,420 volts when the load is disconnected, the voltage difference is 2,420—2,200, or 220 volts, and the voltage regulation is 220 ÷ 2,200, which is 0.10 or 10%.

The drop in line voltage when load is applied is caused by the flow of current through the impedance (reactance and resistance) of the armature winding, and consequently we cannot neglect armature impedance in this study of commercial alternators. The reactance includes the self-reactance of the armature winding and the equivalent effect of armature reaction. The total reactance is referred to as the *synchronous reactance of the armature*. The total impedance of an actual armature winding, including both the resistance and the synchronous reactance, is called the *synchronous impedance*.

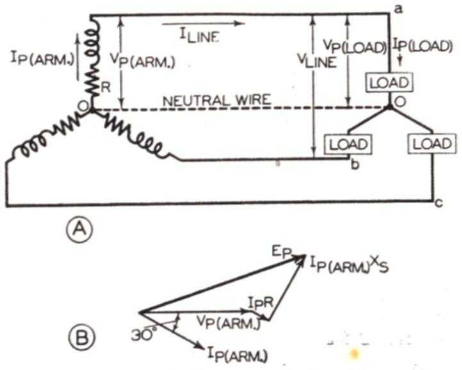


FIG. 8. Circuit of Y-connected three-phase alternator feeding a Y-connected load, and its vector diagram for a balanced inductive load having a power factor angle of 30°.

The three loads on a three-phase alternator may be connected either in Y or Δ, just as in the case of armature windings. For a Δ connection, one load is connected between each pair of lines. For a Y connection, one terminal of each load is connected to a common point, and each other load terminal is connected to one of the three line wires.

When dealing with three-phase circuits, it is convenient to deal with vector diagrams which refer to phase voltages and phase currents rather than to line voltages and line currents. The phase values can easily be derived from the line values, so this introduces no difficulties. Since most loads are balanced, only a single phase need be considered, and the vector diagram is very much simplified.

Let us consider a Y-connected, three-phase alternator feeding a balanced three-phase, Y-connected inductive load having a power factor angle of 30°, as shown in Fig. *8A*. Vectors $V_{P(ARM.)}$ and $I_{P(ARM.)}$ in Fig. *8B* represents the *terminal voltage* and the current respectively of one armature phase. $I_{P(ARM.)}$ lags $V_{P(ARM.)}$ by 30° due to the inductive load on the phase. In flowing through the phase winding, $I_{P(ARM.)}$ causes one voltage drop due to the armature resistance per phase (R), and a second voltage drop due to the armature synchronous reactance per phase (X_S). The $I_{P(ARM.)}R$ drop will be in phase with $I_{P(ARM.)}$, and the $I_{P(ARM.)}X_S$ drop will be 90° **out of phase with $I_{P(ARM.)}$. When the** vectors for these two voltage drops are added vectorially to the terminal voltage $V_{P(ARM.)}$ for a phase, the result is phase voltage E_P, *the voltage which must be induced in the armature phase winding* **to meet the requirements of the load.**

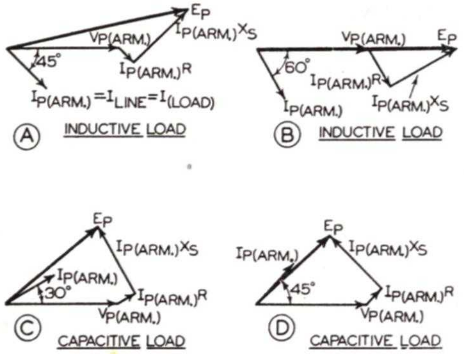


Fig. 9. Vector diagrams for the three-phase alternator circuit in Fig. 8A with four different types of balanced Y-connected loads.

For the conditions represented in Fig. *8B*, the terminal voltage $V_{P(ARM.)}$ is smaller than the induced voltage E_P by the voltage drops in the armature phase winding. If the load were removed, $I_{P(ARM.)}$ would be zero, there would be no voltage drops in the armature, and $V_{P(ARM.)}$ would equal E_P. The per cent voltage regulation is therefore expressed by the following formula, in which E_P is the induced voltage in a phase and $V_{P(ARM.)}$ is the terminal voltage for a phase:

$$\%\ \text{regulation} = 100 \times \frac{E_P - V_{P(ARM.)}}{V_{P(ARM.)}}$$

The vector diagrams in Fig. *9* are all for the armature and load connections of Fig. *8A*, but each is for a different load power factor. In Fig. *9A* the armature phase current $I_{P(ARM.)}$ lags the terminal voltage per phase $V_{P(ARM.)}$ by 45°, and the resulting value of E_P is much greater than for the 30° lag angle in Fig. *8B*. This means that *the greater the angle of lag, the worse is the voltage regulation.* Further verification of this statement is given in Fig. *9B*, where $I_{P(ARM.)}$ lags $V_{P(ARM.)}$ by 60°; here E_P is larger than in both other cases, and voltage regulation is correspondingly worse.

On the other hand, when $I_{P(ARM.)}$ *leads* $V_{P(ARM.)}$, as in Fig. *9C*, the difference between E_P and $V_{P(ARM.)}$ becomes much less. This means that the voltage regulation becomes better when the power-factor angle is leading instead of lagging. When $I_{P(ARM.)}$ leads **$V_{P(ARM.)}$ sufficiently (see Fig. *9D*), E_P** becomes smaller than $V_{P(ARM.)}$; in this case an increase in load will actually increase the terminal voltage $V_{P(ARM.)}$. The voltage regulation is then said to be *negative*, whereas it was *positive* for all of the other conditions shown in Figs. *8* and *9*. A capacitive load

($I_{P(ARM.)}$ leading $V_{P(ARM.)}$) is of value in correcting for excessive voltage drops in the armature windings of an a.c. generator.

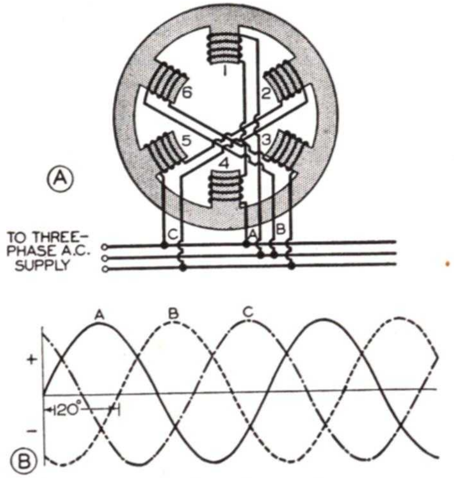


Fig. 10. Stationary armature of a three-phase a.c. motor, and wave form of the three-phase a.c. voltage applied to it.

Armature Reaction in Three-Phase Alternators. The effect of armature reaction is less important in three-phase alternators than in d.c. generators. Since a commutator is not needed, there are no problems involving faulty commutation, sparking at the brushes, and the like. The only effect of the armature flux is to weaken (or strengthen) the main field, thereby affecting the induced voltage. This factor has been taken care of, in the vector diagram of Fig. *8B*, by lumping the effect of armature reaction into the synchronous reactance of the armature.

Power and Power Factor in Three-Phase Systems. The power delivered *to each phase* of a three-phase load is equal to $V_{P(LOAD)} \times I_{P(LOAD)} \times$ load power factor. The total power delivered to the three phases is three times the power delivered to each phase. **The** total power delivered to a three-phase load is therefore: $P = 3 \times V_{P(LOAD)} \times I_{P(LOAD)} \times$ load power factor. (In calculations, power factor is expressed as a decimal less than 1 rather than as a percentage.) If the load is connected in delta, the load phase voltage $V_{P(LOAD)}$ is equal to the line voltage V_{LINE}, and I_{LINE} is equal to 1.73 $I_{P(LOAD)}$. If the load is connected in Y, $V_{LINE} = 1.73\ V_{P(LOAD)}$ and $I_{LINE} = I_{P(LOAD)}$. In either case, the power expressed in terms of the *line voltage* and *line current* is:

$$P = 1.73 \times V_{LINE} \times I_{LINE} \times \text{power factor}$$

Three-Phase A.C. Motors

The Three-Phase Revolving Field. Now let us see how a magnetic field may be set up which revolves in space even though the electrical windings producing this field remain stationary. Consider the stationary armature of a three-phase a.c. motor, shown in Fig. *10A*, to be connected to a three-phase a.c. line which provides the voltages shown in Fig. *10B*. The two poles for each phase are directly opposite each other on the armature, indicating that this armature is designed to operate with a two-pole d.c. rotating field structure such as that shown in Fig. *12A*.

We shall first consider the magnetic field produced by phase winding *A*, consisting of coils *1* and *4* in series. The current set up in this winding by phase voltage *A* of Fig. *10B* will lag the applied voltage by 90° because the winding is essentially inductive. The current in phase *A* for one complete cycle is shown in Fig. *11A*. This current I_A, flowing through coils *1* and *4*, will set up a magnetic field which makes coil *1* north and coil *4* south when the current flows in one direction, and makes coil *4* north and coil *1* south when the direction of the current flow is in the opposite direction. The direction of the magnetic field thus reverses for each half-cycle of the current. Furthermore, since the current changes continuously in magnitude, the strength of this field will vary accordingly. The heavy arrows in Fig. *11A* show the direction and strength of this field at different instants of time during one a.c. cycle. The arrows point in the directions of the fields, and the lengths of the arrows indicate the strengths of the fields. It is seen that for the complete cycle shown, the field produced by phase *A* starts with maximum strength in one direction, reduces to zero, increases to maximum strength in the opposite direction, reduces to zero again, and finally increases to maximum strength in the original direction.

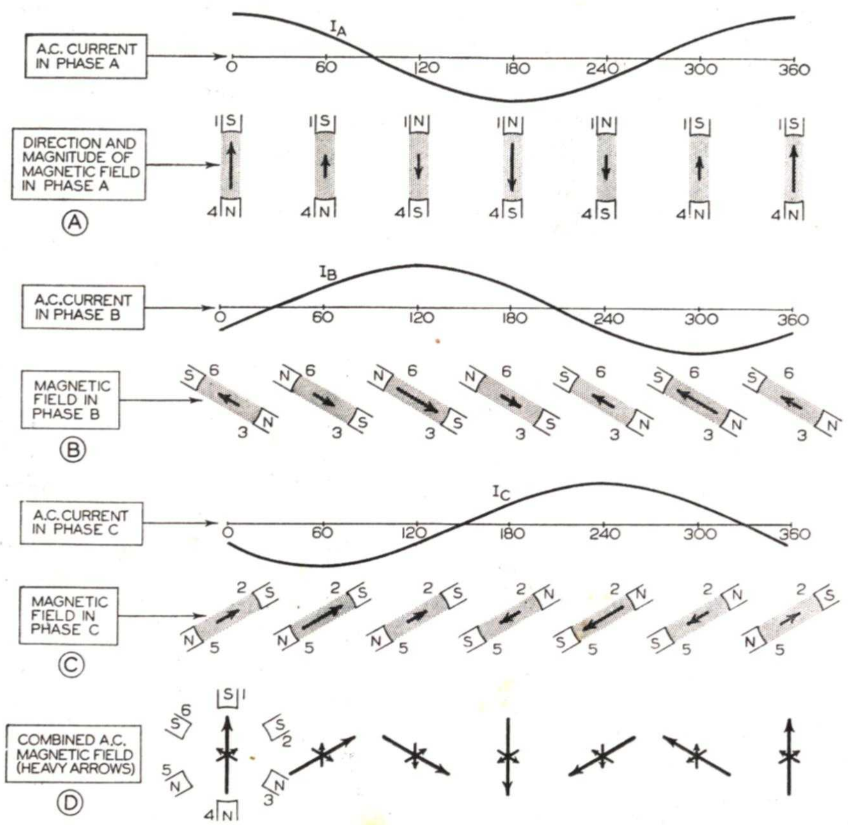


Fig. 11. These diagrams show how the revolving a.c. magnetic field at *D* is produced by the stationary armature of a three-phase a.c. motor.

Phase *B*, consisting of coils *3* and *6* in series, produces a similar varying magnetic field, but since current I_B in this phase is 120° out of phase with the current in phase *A*, the variations in the magnitude and direction of the field will also be 120° out of phase with those in phase *A*. This is shown in Fig. *11B*, where the field produced by phase *B* reaches its maximum values (and its zero values) 120° after the field produced by phase *A* has reached these values. Since coils *3* and *6* are in different space positions on the armature from coils *1* and *4* (see Fig. *10A*), the direction of the field produced by phase *B* intersects the direction of the a.c. field produced by phase *A* at an angle of 120°.

Next consider the field produced by phase *C*, comprising coils *2* and *5* in series. Current I_c flowing in this winding (for one cycle) is shown in Fig. *11C*. The corresponding magnitudes and directions of the magnetic field for phase *C* are shown by the arrows in Fig. *11C*. This field lags the field of phase *B* by 120°, and lags the field of phase *A* by 240°. Again, because of the space positions of coils *2* and *5* on the armature, the direction of the field of phase *C* intersects the other two fields at 120°.

Now let us combine the three fields and find out what net result is obtained. This is done in Fig. *11D* by superimposing the three sets of arrows on each other. Combining these arrows graphically, we see that the resultants will have the directions of the heavy arrows in Fig. *11D*, and their magnitudes will remain constant over the complete cycles of variations of the currents flowing in the armature windings. The resultants represent the combined field produced by the three phase windings. We thus see that a stationary three-phase armature can produce a resultant magnetic field which is of constant strength but changes continuously in direction, so that it makes one complete revolution in space *for each cycle of the a.c. supply voltage.*

Three-Phase Synchronous Motor

Two-Pole D.C. Field System. Now assume that a two-pole d.c. field structure like that in Fig. *12A*, energized by a d.c. source through slip rings and brushes, is placed so that it can rotate

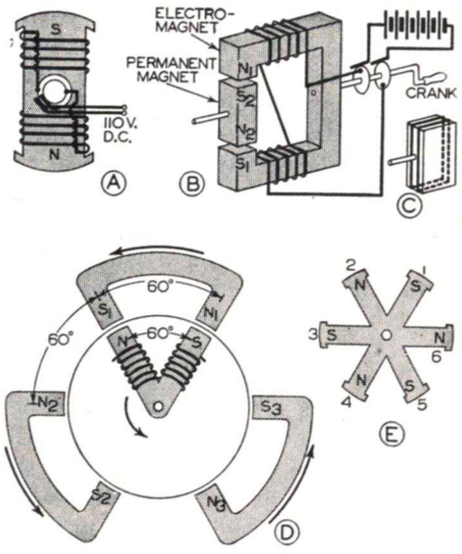


Fig. 12. Elementary structures of three-phase synchronous motors.

within the stationary armature* of

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*The armature in a motor can be defined as that part which receives the most electric power from the main power line. The armature may be either stationary or rotating.

A clear understanding of the distinction between the words "rotate" and "revolve" will help you to follow this discussion. An object "rotates" about its own axis, and "revolves" about another object. The field produced by the stationary armature therefore *revolves* around the d.c. field structure. The field produced by the d.c. field structure, on the other hand, is a *rotating* field since it moves around its own axis. Here is an analogy: The earth *rotates* about its own axis, but *revolves* around the sun.

Fig. *10A*. This gives a three-phase synchronous motor; let us see how interaction of the d.c. field with the revolving field produced by the stationary armature results in rotation.

First consider the simplified version of this motor in Fig. *12B*, in which the permanent magnet N_2-S_2 represents the two-pole rotating d.c. field structure and electromagnet N_1S_1 represents the revolving field set up by the three-phase a.c. armature. The permanent magnet is free to rotate about its shaft, and the electromagnet is provided with a crank so it can be rotated to duplicate the effects of the revolving field set up by the stationary armature.

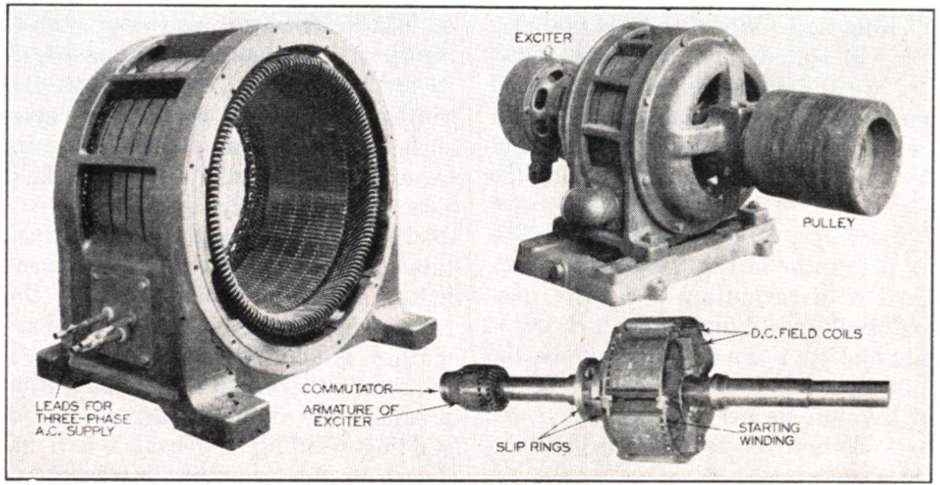
Let the electromagnet be turned slowly until its north pole attracts the south pole of the permanent magnet. The two fields then *lock* together in the position shown in Fig. *12B*. Now, as the crank is gradually turned faster and faster, the permanent magnet will rotate at the same speed. When the crank reaches and holds a definite rotational speed (say 3,600 r.p.m.), the permanent magnet will rotate at that same speed, almost as if it were mechanically coupled to the electromagnet. This corresponds to operating conditions in a synchronous motor.

Now suppose that at the start you prevented the permanent magnet from rotating by holding it with your hand until the electromagnet reaches its operating speed (3,600 r.p.m.). Upon releasing the permanent magnet, you would find that it would not rotate due to its mechanical inertia (its tendency to remain at rest). During one half-revolution, pole N_1 would tend to move S_2 in one direction, but the inertia of the permanent magnet would prevent it from following the revolving field very far. During the next half-revolution, pole N_1 would be acting on S_2, tending to rotate the permanent magnet in the opposite direction. The net result is that the permanent magnet remains at rest or vibrates slightly back and forth. This is exactly the condition we have in a synchronous motor if special means are not provided for starting.

Now assume that several closed loops of copper are placed lengthwise over the permanent magnet in the manner shown in Fig. *12C*. The revolving field produced by the electromagnet changes the flux linkages in these closed circuits, inducing voltages in them. These voltages produce currents which in turn produce magnetic fields which react with the revolving field to start the permanent magnet in motion. The torque is greatest when the coil is at rest because the flux linkages are then changing at a maximum rate, making the induced voltage a maximum. A powerful twisting action is thus exerted on the permanent-magnet rotor, speeding it up rapidly. The torque decreases as the difference between the speed of the rotor and the revolving field becomes less and less, but this torque is no longer needed once a speed is reached at which the rotor *locks into step* with the revolving field. This is the principle of the self-starting synchronous motor. The rotor then rotates at the same speed as the revolving field (at *synchronous speed*).

The two-pole d.c. field structure in Fig. *12A* obviously produces exactly the same field as the permanent magnet in Fig. *12B*. When this two-pole d.c. field is placed inside a revolving field (produced by the elementary rotating electromagnet in Fig. *12B* or by a three-phase stationary armature), and this d.c. field is brought up to speed by some means, it will lock in step and continue rotating at synchronous speed.

The field produced by the three-phase stationary armature in Fig. *10A* makes one complete revolution per a.c. cycle, and the d.c. field structure (the rotor) will therefore make one revolution per cycle also. This means that if 60-cycle-per-second power is applied to the motor, the rotor speed will be 60 revolutions per second, or 3,600 r.p.m. (60 × 60 = 3,600).



Courtesy General Electric Co

Typical three-phase general-purpose synchronous motor as made by General Electric Co. The photograph at the left shows how the three windings of the stationary armature are uniformly distributed around the circumference. This machine generates its own power for the rotating d.c. field by means of an exciter (small d.c. generator) mounted directly on one end of the rotor shaft. The rotating d.c. field has six poles, with copper bars embedded in the pole faces and connected together to form a squirrel-cage winding for starting purposes. At synchronous speed no currents flow in the starting windings because the rotor is then traveling at the same speed as the stator-produced revolving field, and there is no change in flux through the starting windings. Synchronous speed is 1200 r.p.m.

Multi-Polar Synchronous Motors. If the stationary armature coils of Fig. *10A* were moved closer together, so that all six coils covered only one-third of the circumference of the armature, the revolving field produced by this stationary armature would sweep by the complete set of six stationary armature coils in the time corresponding to one cycle of the applied a.c. voltage, but this would represent only one-third of a revolution. By placing two additional similar sets of windings on the armature and connecting them properly to the first set, we can secure a revolving field which will make one complete revolution every three cycles. We can consider the three sections of the armature as being equivalent to three horseshoe-shaped electromagnets revolving around the rotor at the rate of one revolution per three cycles, just as in Fig. *12D*.

Now let us squeeze together the two-pole d.c. rotor of Fig. *12A* in a corresponding manner so its poles will be 60° rather than 180° apart. We place this V-shaped rotor structure in the three-section stationary armature of Fig. *12D*, and bring the rotor up to the speed of the revolving field by some means. The rotor will immediately lock in step with one of the three revolving electromagnets (such as with N_1-S_1), and will then continue to rotate at the same speed (one revolution every three cycles). But we have two other revolving electromagnets which could be doing useful work; let us place a V-shaped rotor structure in front of each, giving six d.c. poles on the rotor, as in Fig. *12E*. Now each d.c. pole will contribute torque to the rotor, and we obtain three times as much mechanical power from the motor as we would with the two-pole arrangement in Fig. *12D* without changing the speed.

Speed of a Three-Phase Motor. The six-pole rotor in Fig. *12D* makes one-third of a revolution per cycle, just as does the revolving field which keeps it in motion. For a 60-cycle supply, the rotor speed is therefore 1/3 × 60, or 20 revolutions per second; this gives 20 × 60 or 1,200 revolutions per minute.

The speed of any three-phase a.c. motor can be determined by the same formula as was used for a three-phase a.c. generator:

$$\text{Motor speed in r.p.m.} = \frac{120f}{P}$$

In this formula, f is the frequency of the supply voltage and P is the number of d.c. field poles. If $P = 6$ and $f = 60$, the motor speed in r.p.m. is $120 \times 60 \div 6 = 1{,}200$ revolutions per minute.

Starting Three-Phase Synchronous Motors. Except for the lower rotational speed, the operation of a multipolar synchronous motor is identical with that of a two-pole machine. Once the d.c. field structure is brought up to synchronous speed, its field will lock with the revolving field of the armature, and the rotor will continue rotating at synchronous speed.

In construction, the commercial synchronous motor does not vary greatly from a commercial alternator of the stationary-armature, rotating-field type. The essential difference is in the starting winding (variously called a *damping* winding, an *armotisseur* winding, or a *squirrel-cage* winding), but some alternators also have a winding like this for maintaining a constant frequency (see Fig. *7B*).

When starting a three-phase synchronous motor equipped with a squirrel-cage starting winding, the d.c. field circuit is generally opened and reduced voltage is applied to the armature. In this way the starting current in the armature, limited only by the resistance and self-reactance of the armature, is kept within safe limits. As the rotor gains speed due to the torque produced by induced currents in its starting winding, the back e.m.f. induced in the armature increases, so that the applied voltage may gradually be raised to its normal value. *When the motor approaches synchronous speed,* the d.c. field circuit is closed; the rotor then pulls in to synchronous speed.

While a starting winding may be designed to produce considerable starting torque, practical considerations such as that of space for the winding set definite limits on the amount of starting torque which can be secured. The synchronous motor is therefore most useful for handling loads which can be applied after the motor is up to speed.

Operating Characteristics of Synchronous Motors. When a constant-speed drive with variable torque is required, the three-phase synchronous motor is particularly applicable. The rotor speed cannot decrease as load is applied since this machine *must* operate at synchronous speed, and hence some other change must occur which will permit an increase in current flow through the armature to take care of an increased shaft load. This change is actually a slight shifting of the rotor (backward against the direction of rotation), so that the phase of the induced voltage is shifted. The vector diagrams in Figs. *13A* and *13B* show how this provides for increased armature current and increased torque.

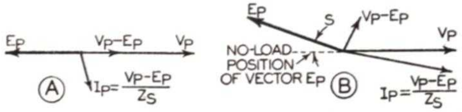


FIG. 13. Vector diagrams for no-load (*A*) and loaded (*B*) conditions in a three-phase synchronous motor.

In Fig. *13A,* the induced voltage (back e.m.f.) E_P per phase in the stationary armature is 180° out of phase with the applied voltage V_P per phase, and is lower in value. The difference $(V_P - E_P)$ serves to force current through the synchronous impedance of the armature. The armature current I_P per phase lags this net voltage by nearly 90° because the armature winding is highly reactive. This is the current available to develop torque at the rotor shaft. Now, referring to Fig. *13B,* suppose that the rotor has shifted its position with respect to the revolving armature field by the angle S. This makes the vector difference between V_P and E_P much greater than before, giving a higher armature current I_P per phase and consequently a higher torque. Note that the power factor is also improved (the angle between vector V_P and vector I_P is considerably less than 90°). The maximum torque which can be developed is limited by the fact that after the shift angle S has exceeded 90°, the rotor will fall out of synchronism and will gradually come to rest. The torque causing this condition is termed the *pull-out torque.*

The correction of the power factor of highly inductive loads is a major use for the synchronous motor. This is accomplished by making the synchronous motor take a current which *leads* the applied voltage, making up for *lagging* currents taken by the inductive loads. The synchronous motor is generally operated at little or no load and high field excitation for this type of service, and is referred to as a *synchronous condenser.* In any three-phase synchronous motor, the phase angle between the applied voltage and the motor current can be varied *by varying the d.c. field current for the motor.* The reason for this will be apparent from a consideration of the vector diagrams in Figs. *14A* and *14B*.

Referring to Fig. *14A*, let the d.c. field excitation be low. The induced voltage E_P in the armature is then smaller than the terminal voltage V_P, and the net voltage $(V_P - E_P)$ is practically in phase with V_P. Armature current I_P, which lags the net voltage, also lags V_P in this case (a lagging power factor angle). Referring next to Fig. *14B,* let the field excitation be high. This makes E_P larger than V_P, and the net voltage $(V_P - E_P)$ is almost 180° out of phase with V_P. I_P, which lags the net voltage, now leads V_P (a leading power factor angle). While these diagrams are for no-load conditions, they are modified only slightly for light loads.

It is of interest to note that actual condensers may be used for power-factor correction in place of the synchronous motor. Because of the high cost of large condensers which are capable of handling heavy currents, however, this practice is limited to low-power loads.

Three-Phase Induction Motors

The use of short-circuited loops on the d.c. field structure of a synchronous motor for starting purposes has already been discussed. When the short-circuited loops alone are used as the rotor, the device becomes known as an *induction motor*. The conventional type of three-phase induction motor consists of a stator which is in every way similar to the stationary armature of a three-phase synchronous motor, and either a wound rotor or a squirrel-cage rotor with bearings to support it.

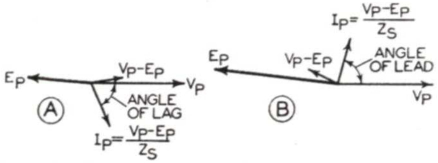


FIG. 14. Vector diagrams for a three-phase synchronous motor having low d.c. field excitation (*A*) and high field excitation (*B*, corresponding to a synchronous condenser).

Three-Phase Squirrel-Cage Induction Motor. The stator of a typical squirrel-cage induction motor is shown in Fig. *15A*, and its rotor appears in Fig. *15B*. The stator consists of a laminated sheet steel core having slots for the carefully insulated coils. The rotor core is also made up of sheet steel laminations, either mounted directly on the shaft or on a spider on the shaft. The rotor windings usually consist of heavy copper bars connected together at each end by a ring. Small motors sometimes have the windings and end rings cast together in one operation. No insulation other than natural oxidation is required between the bars and the core because of the low voltages involved.

The air gap between the rotor and the stator must be very small to get the best efficiency. The shaft must therefore be very rigid and furnished with the highest grade bearings. The three-phase, squirrel-cage induction motor is one of the most efficient motors built (whether a.c. or d.c.), being exceeded in efficiency only by large synchronous motors.

The principle of operation of the induction motor has been outlined to you in an earlier lesson. The revolving stator field sweeping by the short-circuited loops of the rotor induces voltages in these loops. The resulting currents set up magnetic fields which interact with the revolving stator field to produce motion of the rotor. The torque decreases gradually as the motor builds up speed, and finally a condition of equilibrium is reached whereby the speed at which the revolving stator field is sweeping by the rotor (i.e., the slip) is just sufficient to set up the right amount of current in the rotor to handle the torque of the load on the rotor shaft. If the load is decreased, less torque is required and the rotor speeds up until the current in it is sufficiently reduced. If the load is increased, more torque is required, and the rotor slows down (slips back) until the current in it is sufficiently increased.

As has already been pointed out, three-phase induction motors have exactly the same stationary armatures as three-phase synchronous motors. When the stationary armature of a *two-pole* synchronous motor is used for an induction motor, we say that the induction motor has two poles; likewise a four-pole induction motor would have the same stator as a four-pole synchronous motor, etc. Obviously this number-of-poles designation for induction motors refers to the stator connections, for there are no d.c. poles.

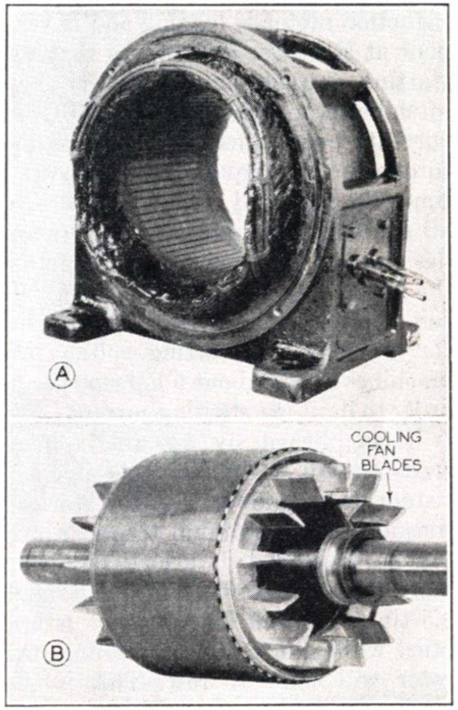
The speed of an induction motor is always less than the speed of the revolving field (less than synchronous speed). The difference between the synchronous speed and the actual speed of an induction motor is called the *slip*. With a 60-cycle supply, a two-pole induction motor has a synchronous speed of 3,600 r.p.m. and has a full-load speed of about 3,450 r.p.m. A four-pole machine has a synchronous speed of 1,800 r.p.m. and a full-load rotor speed of about 1,725 r.p.m. Synchronous speeds for induction motors with more than four poles can be determined by the same formula as for synchronous motors. Full-load speed will generally be about 5% less than synchronous speed.

The slip in an induction motor is generally expressed as a per cent of the synchronous speed; thus, for a four-pole, three-phase squirrel-cage motor, running at 1,725 r.p.m. under load, the per cent slip would be:

$$\%\ \text{slip} = \frac{1{,}800 - 1{,}725}{1{,}800} \times 100$$

$$= .0417 \times 100 = 4.17\%$$

Since the rotor loop is short-circuited, the product of the induced voltage and the current in the rotor represents an I^2R loss. The slip is therefore a measure of the rotor I^2R losses; the higher the slip for a given load, the higher are these losses and the less efficient is the motor.



Courtesy General Electric Co.

FIG. 15. Stator (*A*) and rotor (*B*) of a typical squirrel-cage type three-phase a.c. induction motor.

The starting torque of a squirrel-cage motor is the turning effect or torque which the rotor exerts when full voltage is applied to the stator winding with the rotor at rest. The amount of starting torque developed depends upon the resistance of the rotor winding. A higher rotor resistance gives a higher starting torque, with a corresponding increase in slip (at normal rotor speed) and a decrease in efficiency.

The power factor of a squirrel-cage induction motor is lagging and is very poor at starting. This means that the starting current (in the stator) may often be six to eight times the full-load current even though the starting torque is only equal to at most 1.5 times the full-load torque. Practically all squirrel-cage induction motors are designed to be thrown directly across the line at full voltage for starting, but some power companies insist on means for reducing the starting voltage for machines above about 5 horsepower in order to limit the starting current. This is accomplished by variable-voltage transformers or by variable line resistors. It is obvious that the starting torque is the maximum torque which can be developed. If a load requiring more than the starting torque (about 1.5 times the full-load torque) is applied while the motor is running, the rotor will come to rest. This is the "pull-out" torque for the induction motor.

The power factor of an induction motor is best at full load. At smaller and greater loads, the power factor decreases. If too large or too small a motor is used for a given load, the stator current will be greater than necessary, and efficiency will be low. It is important to choose a motor size corresponding to the load to be handled, whenever the service permits.

Wound-Rotor Type Three-Phase Induction Motor. Where adjustable-speed operation with induction motors is required, or where high starting torque with efficient operation at normal speed is required, the wound-rotor type induction motor is generally employed. It differs from the squirrel-cage type only in the rotor winding, as can be seen by referring to the photographs in Fig. *16* of a typical wound-rotor machine. The rotor winding consists of insulated coils, wound identically with the stator windings (having the same number of poles) and having the terminal connections of these windings brought out to three slip rings. Leads are run from the brushes on the slip rings to an external adjustable resistance unit.

High starting torque is obtained in a wound-rotor type three-phase induction motor *by inserting resistance in the rotor windings.* For starting service, this external resistance may be rated for intermittent duty only. It is inserted in the rotor windings only at starting, to correct the power factor and thereby to increase starting torque for a given stator starting current. As the rotor comes up to speed, the resistance is gradually cut out.

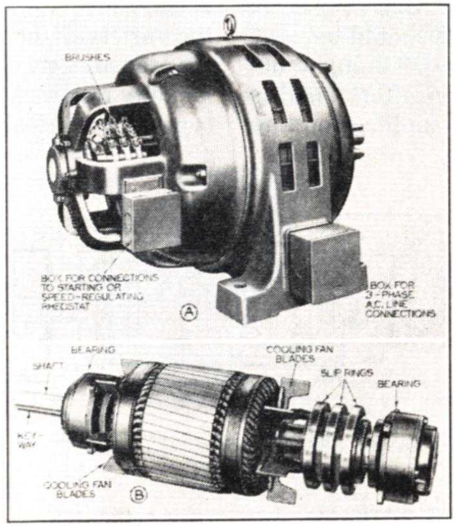
For adjustable-speed operation, the resistance must be of the continuous-duty type. For a given load, the rotor speed may be varied by inserting resistance, since the greater the rotor resistance the greater must be the slip in order to develop the required torque. This method of adjustable-speed operation is not as satisfactory as is obtained with d.c. motors since the speed will vary with any variation in the load. However, it is one of the best of the few speed-controlling methods available for a.c. motors.

Motor-Generator Sets

We have thus far studied the most important types of motors, generators and alternators. Now let us turn our attention to combinations of motors and generators, known as motor-generator sets.

As the name implies, a motor-generator set is a combination of dynamo-electric machinery including a driving force (an electric motor of the a.c. or d.c. type) and one or more a.c. or d.c. generators. There are various combinations of motors and generators in motor-generator sets. A d.c. compound motor may drive a d.c. shunt generator; a d.c. compound motor may drive a d.c. compound generator; in fact, you may find any type of d.c. or a.c. motor driving either a d.c. generator or an alternator.

A motor-generator set may consist of only one unit having two bearings, with the motor and generator armatures being adjacent to each other, keyed and locked on the same shaft, or it may consist of two separate units mounted on a common base. In the latter case, the shafts of the motor and generator are joined by a flexible coupling, and each unit has its own pair of bearings. One motor is sometimes used to drive two or more generators which are joined to it by flexible couplings.



Courtesy Fairbanks-Morse and Co.

FIG. 16. Typical wound-rotor type three-phase a.c. induction motor (*A*). The rotor of this machine is shown at *B*.

Motor-generators have many uses; they can convert low-voltage d.c. to high-voltage d.c., convert low-voltage d.c. to high- or low-voltage a.c., convert a.c. to high- or low-voltage d.c., or convert a.c. of one frequency to a.c. of another frequency. Motor-generators for converting a.c. of one voltage to a.c. of another voltage, while possible, are not necessary in view of the much greater flexibility and efficiency of transformers.

Since we have studied the characteristics of all of the individual machines which may make up a motor-generator set, it is not necessary to discuss details of the operating characteristics of the various possible combinations. The requirements of the service, the nature of the power supply available and the type of load will generally determine what types of motors and generators should be used.

A few points may be brought out about the small exciter often found in a motor-generator combination for furnishing field current to the various machines. Where d.c. power is used at the motor end, the exciter is naturally omitted. However, when high-voltage d.c. generators are employed, a low-voltage exciter is often used, for the high d.c. voltages would impose severe insulating requirements on the field windings.

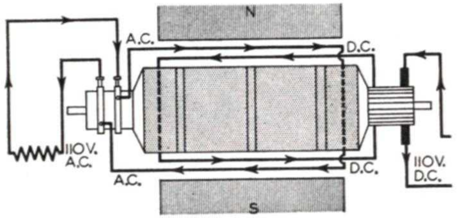


FIG. 17A. Simplified circuit of a dynamotor.

Motor-generator sets were once widely used at broadcast stations to furnish the various d.c. voltages required by the radio transmitter. With the advent of efficient rectifier systems and the general availability of a.c. power supplies, the use of motor-generator sets in broadcast stations is now largely obsolete. The available a.c. is now transformed to the required voltages and rectified.

There are still many isolated regions where no electrical power supply is available, and metropolitan areas where only d.c. is available. In the former case, a gasoline engine-driven a.c. generator is used together with transformers and rectifiers. In the latter case, the d.c. must first be converted into a.c., which may then be transformed and rectified to supply the variety of d.c. voltages required by the transmitter. A motor-generator set is here required, or one of the two types of electrical machines treated in the following section may be employed.

Dynamotors and Rotary Converters

Two special types of machines, the *dynamotor* and the *rotary converter,* have been designed to develop low-power, single-phase currents from d.c. power or give the reverse conversion. Each type is built as a single unit having only one armature and two bearings, the field being common to both motor and generator.

The fundamental circuit of a dynamotor is given in Fig. *17A*. Two entirely separate windings are used on the rotating armature. Direct current from the line enters the armature through a standard commutator and brushes, just as in a regular d.c. motor. As the armature rotates in the magnetic field, the other winding is operated under conditions satisfactory for generator action, and consequently an e.m.f. is generated in that winding. This armature winding may be led out either through commutators for d.c. generation or through slip rings (as shown at the left in Fig. *17A*) for a.c. voltage generation. The separate generator windings may even be wound in the same armature slots as the motor windings.

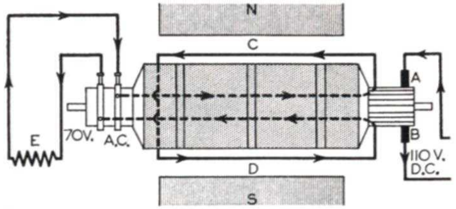


FIG. 17B. Simplified circuit of a rotary converter. The winding elements are connected to commutator segments just as in a d.c. motor or generator (only one winding element, with conductors *C* and *D*, is shown), and the ends of the armature winding are connected to the two slip rings at the left by means of leads running through holes near the center of the armature (shown dotted in the above diagram).

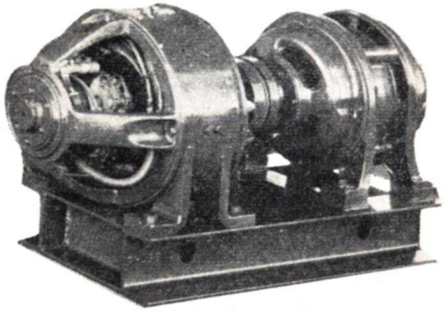
In general, alternating current is produced in the second winding of a dynamotor and is fed to the load through slip rings. Machines of this kind are used extensively for a.c. filament supplies because of their extreme simplicity and compactness. In territories where only d.c. voltage is available, small dynamotors may be used to convert 110-volt d.c. to 110-volt a.c. to operate a.c. socket-powered receivers or low-power transmitters.

The rotary converter is even more simple. The rotating armature of the rotary converter has only one winding, as indicated in Fig. *17B*. The commutator is placed on one end of this armature, and a set of slip rings is mounted on the other end of the shaft, so that direct current can be fed into the armature and alternating current taken from it. We have shown in an earlier lesson that a wound armature with slip rings may be used as a single-phase a.c. generator or motor, while a wound armature with a commutator may be used as a d.c. generator or motor. In the rotary converter, slip rings and a commutator are connected to the same armature so that it can act as a d.c. motor and a single-phase a.c. generator at one and the same time.

When a motor-generator combination can be built as one machine, obviously it will be less expensive than two separate devices. Dynamotors and rotary converts are used extensively for low-power purposes, but are not recommended for powers exceeding 500 watts. Both devices have the disadvantage that they do not allow full control over the output voltage.

The dynamotor is in widespread use in mobile radio installations such as in airplanes, automobiles, water craft and the like, where the only power supply available is a low-voltage storage battery. The dynamotor is used to convert this low d.c. voltage to the higher d.c. voltages required. Often the dynamotor has three windings, one for the motor and two for generators. A typical airplane installation might have a 12-volt battery, a 12-volt d.c. motor winding on the dynamotor, a 220-volt d.c. generator winding on the dynamotor for the receiver plate supply, and a 1,050-volt d.c. generator winding on the dynamotor for the transmitter plate supply. Filament power for receivers and transmitters is taken from the storage battery.

Maintenance of Motors and Generators



Courtesy General Electric Co.

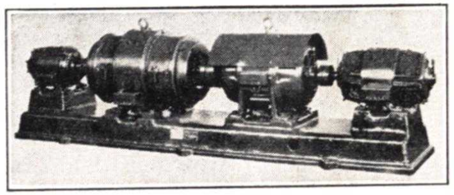
This General Electric motor-generator set is one of a group of similar two-unit sets now being used to supply filament power and bias voltages for the RCA television transmitter in New York City. In each set an a.c. motor connected to the power line drives a low-ripple d.c. generator.

Difficulties which arise in the maintenance of electrical machinery are largely due to incorrect operation and insufficient care of the important components. The proper maintenance procedures for different types of machines are generally provided by the manufacturers of these machines, and should be rigorously followed. The following paragraphs deal with a few of the more common maintenance problems encountered.

Sparking at Brushes. The causes for sparking at brushes in a motor or generator are: overloading, wrong setting of brushes, poor brush contacts or connections, rough, worn or corroded commutator, weak field magnetism, insufficient under-cutting of mica, and a partially open or shorted armature winding. A careful examination will generally reveal the defective condition. An ordinary ohmmeter will be very helpful for checking continuity. One important word of caution: *Never use emery cloth on the commutator of any electrical device*. The carbon particles which come off the emery cloth may bridge the commutator segments and short-circuit the armature. Use fine sandpaper (about 00 grade) instead.

Hot Armature or Field Coils. Overheating of the armature or field coils can generally be traced to overloading, to damp windings which result in insulation break-down, or to short-circuited coils. The rewinding of a defective armature is a job for a professional armature winder, and should not be attempted by the radio operator except in extreme emergencies.

Hot Bearings. This is the most important of all maintenance problems. The shaft of a machine is generally made of steel, whereas the bearing surface which carries the shaft is made of "babbitt," an alloy metal which is just plastic enough to be molded into shape by the shaft, or of bronze.* The length of each bearing is approximately twice the diameter of the shaft, so as to reduce the pressure per unit area of bearing surface. Small diagonal grooves are often cut in the inside surface of the bearing to permit lubricating oil to cover the entire bearing surface.



Courtesy General Electric Co.

A four-unit, eight-bearing G. E. motor-generator set capable of providing all d.c. power required by a medium-size radio station. A 9-h.p., 1800-r.p.m. a.c. induction motor drives a 3.8-kw., 1500-volt d.c. plate supply generator, a .3-kw., 500-500-volt d.c. bias generator and a .5-kw., 23-volt filament generator which also provides excitation power for the other two generators.

Overheating of bearings on motor-generator sets may be caused by lack of lubrication, bearings fitting too tightly, eccentric or flattened shaft, or coupling units off center. Babbitt metal melts at fairly low temperatures. In some cases the bearing will heat up to the melting point of the babbitt and the entire bearing will be destroyed. When a bearing shows signs of serious overheating, and burns the lubricating oil furnished to it, an abundance of oil should be applied immediately and the apparatus reduced in speed *but not stopped*. Do not stop the motor or generator without an application of oil. If the unit is stopped while the bearing is still hot and dry, the bearing metal may melt and mold itself to the shaft, destroying the bearing and making it extremely difficult to start the apparatus again. Every means possible should be employed to cool the bearing while the appartus is still running slowly. A cloth dipped in cold water should be applied or a fan directed toward the bearing. When the bearing has again reached normal temperature, the apparatus should be stopped and inspected. The bearing should then be cleaned and flushed with kerosene or gasoline, refaced if necessary, lubricated and placed in operation.

If a bearing is too hot for the hand to be held on it, or if there is an odor of burning oil about the motor or generator, proceed as follows:

See that the oil cups are full and delivering the proper amount of oil to each bearing. See that the oil is of good quality and that the oil line is clean. Make sure that the oil is free from grit by rubbing a little of it between the fingers. The shaft of a motor, a generator, or a motor-gen-

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***While this discussion is limited to "babbitt" and bronze bearings, essentially the same precautions apply to ball and roller bearings such as are used on smaller machines.**

erator set should always have a sufficient amount of end play. End play is necessary for uniform wear on the commutator and on the bearings. See that the motor shaft is not too tight in the bearing. Note with your eye if the coupling unit is running true in the case of a motor-generator set, and realign the unit if necessary. See that the shaft is perfectly straight. If the shaft is crooked, it must be turned down in a lathe or returned to the manufacturer for correction.

An overheated commutator will also cause a bearing to become overheated in some instances. The commutator will overheat if excessive sparking occurs or if the brush contacts have become defective, causing arcing and high temperature at the brushes. This can be remedied by increasing the tension on the brush or replacing the brush. To prevent too much brush friction on the commutator, a very thin coating of vaseline or petroleum jelly may be applied with the finger tip and renewed every few days as required. This is the only kind of commutator lubrication that is ever recommended. Avoid allowing oil or grease of any kind to touch the commutator.

Lesson Questions

Be sure to number your Answer Sheet 28RC

Place your Student Number on *every* Answer Sheet.

Most students want to know their grade as soon as possible, so they mail their set of answers immediately. Others, knowing they will finish the next Lesson within a few days, send in two sets of answers at a time. Either practice is acceptable to us. However, don't hold your answers too long; you may lose them. Don't hold answers to send in more than two sets at a time or you may run out of Lessons before new ones can reach you.

1. What is the phase angle between the voltages provided by a three-phase alternator?
2. How would you connect together the phase windings of a three-phase alternator to get a delta connection?
3. What two important facts should be stated when discussing an a.c. voltage in an a.c. circuit?
4. In a delta-wound three-phase alternator with balanced loads, what is the relationship between the magnitudes of the line current and the armature current per phase?
5. In a three-phase alternator, which connection (delta or Y) of the phase windings gives higher line voltages?
6. When starting a three-phase synchronous motor which is equipped with a squirrel-cage starting winding, when is the d.c. field circuit closed?
7. In a three-phase synchronous motor, how can the phase angle between the applied voltage and the motor current be varied?
8. What name is given to the difference between the synchronous speed and the actual speed of an induction motor?
9. How is high starting torque obtained in a wound-rotor type three-phase induction motor?
10. Should a motor or generator be stopped immediately when a bearing shows signs of serious overheating?

DIPLOMACY

Diplomacy in its true sense is simply courtesy. A true diplomat is one who shows a deep appreciation of the other fellow's feelings.

A diplomat knows when to agree with you—and how to disagree. He will agree on trivial matters regardless of his own opinions, thereby winning your good will. When it comes to something important, however, he will bring you to his way of thinking—*painlessly*. You will enjoy doing what he requests because he makes you feel that you are an important person.

Now turn matters around—and you be the diplomat. In conversation, be considerate of the other fellow's feelings and pet beliefs. Don't contradict people flatly—nobody appointed you to go around correcting the mistakes of others.

People like the man who thinks before he talks—who doesn't make rash or crude statements. And if you can get people to like you, you can count on them to help you—to give the sort of cooperation that will mean success for you.

So learn diplomacy—and practice it in all your contacts with people.

J. E. SMITH