D.C. AND A.C. SINGLE-PHASE GENERATORS AND MOTORS

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STUDY SCHEDULE NO. 27

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. Dynamo-Electric Machinery in Communications; Fundamental Concepts; Direction of Magnetic Lines of Force . . . . Pages 1-2

This tells the importance of and gives a brief description of a generator and a motor.

☐ 2. Law of Induced Voltage; Force on a Current Carrying Conductor in a Magnetic Field; Energy Laws for Generators and Motors . . . . Pages 2-7

The factors on which an induced voltage depends, and a comparison of motors and generators are given in this section. Answer Lesson Question 1.

☐ 3. Simple, Single-Phase A.C. Generator; a Simple D.C. Generator . . . . Pages 7-10

You study the operation of a single-phase a.c. generator and of a d.c. generator. Answer Lesson Question 2.

☐ 4. Armature Windings; Effect of Armature Reaction on Commutation in a D.C. Generator . . . . Pages 10-15

Lap and wave windings, distortion of the magnetic field as a result of armature reaction are discussed. Answer Lesson Question 3.

☐ 5. Reentrancy of Windings; Winding Pitch and Commutator Pitch; Armature Windings for Single-Phase A.C. Generators; Field Excitation for A.C. and D. C. Generators . . . . Pages 15-16

Single, double, and triple reentrancy, front pitch and back pitch, armature windings, and field excitation are discussed. Answer Lesson Question 4.

☐ 6. Operating Characteristics of the Single-Phase A.C. Generator; Operating Characteristics of the D.C. Generator; Efficiency of Generators . . . . . . Pages 16-19

You study the factors defining the operating characteristics of a generator, voltage regulation, and the efficiency of generators. Answer Lesson Questions 5 and 6.

☐ 7. The D.C. Motors; Commutation in D.C. Motors; Efficiency of Motors . . . . Pages 19-23

You study the characteristics and efficiency of d.c. motors. Answer Lesson Questions 7, 8, and 9.

☐ 8. The A.C. Single-Phase Motor . . . . Pages 23-29

Different types of a.c. motors are taken up in this section. Answer Lesson Question 10.

☐ 9. Start Studying the Next Lesson.

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D.C. and Single-Phase A.C. Generators and Motors

Dynamo-Electric Machinery in Communications

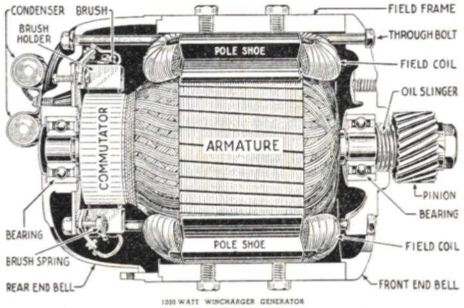
IN all radio installations, whether on land, sea or air, the power supply system employed is of paramount importance—so important that often the very safety of life may depend upon its operation. No radio installation can be more reliable than its power supply, hence it is just as important for the competent radio operator to understand the fundamentals of power supply systems as it is to familiarize himself with the principles of radio transmitting and receiving equipment.

While the use of dynamo-electric machinery at fixed land radio stations is gradually being limited to emergency use only, such machinery must always remain an essential portion of the power supply system in most mobile radio stations, such as in ships, aircraft and automobiles. Any treatment of the subject of power supplies must, therefore, include a discussion of generators and motors. This lesson will deal with the fundamentals of direct-current generators and motors and single-phase, alternating-current generators and motors, so that you will know how to operate these units efficiently and will be able to make simple repairs in case of emergency.

Fundamental Concepts

An electric generator is a machine which converts mechanical energy into electrical energy. In a dynamo-electric generator the mechanical energy usually rotates a system of conductors through a magnetic field, producing at the terminals of the system of conductors an electric voltage which will send current through an externally connected load and thus supply the load with electrical power.

An electric motor is a machine which converts electrical energy into mechanical energy. In a dynamo-electric motor the flow of current through a system of conductors placed in a magnetic field is converted into a motion of these conductors about a shaft. Mechanical power is thus made available at the shaft.



Courtesy Wincharger Corp

Cut-away diagram showing construction of a 1000-watt, 32-volt d.c. generator. This unit is made by the Wincharger Corp., Sioux City, Iowa, for use in wind-driven charging systems for 32-volt farm power plants. This construction is typical of all small d.c. generators. The two condensers suppress sparking at the brushes and thereby prevent radio interference. This particular unit employs a gear drive to the propeller shaft.

Direction of Magnetic Lines of Force

In both types of dynamo-electric machines we have electric circuits, magnetic circuits and motion. The source for a magnetic circuit is generally an electromagnet, in order to make the magnetic field as powerful as possible. The electric circuit, since it carries current, has a magnetic field associated with it (independent of the main magnetic field). We are, therefore, fundamentally interested in the direction of flow of the magnetic lines of force associated with the flow of electrons through an electrical conductor. This relationship is given in Fig. *1A*. The lines of magnetic force correspond in direction to those flowing out of a north magnetic pole and into a south magnetic pole.

Figure *1B* shows a second and perhaps simpler way to remember this relationship between electron flow and magnetic lines of force. If you imagine that you are grasping the electrical conductor in your *left* hand in such a way that your thumb points in the direction of *electron* flow, your fingers will be curled around the wire with the tips pointing in the direction of the magnetic lines of force.

Law of Induced Voltage

A second important relationship is that which tells the magnitude and direction of the voltage produced when a conductor is moved through a magnetic field. Figure *2A* shows a permanent magnet having a north and a south pole close to each other; between the poles is a strong magnetic field acting in the direction of the arrows. A conductor is placed in this magnetic field, and its ends are connected to an instrument which measures the magnitude and direction (polarity) of the voltage induced in the wire. (It is assumed that the instrument requires a very minute current for its operation, in order that we can consider the conductor to be without an appreciable load.)

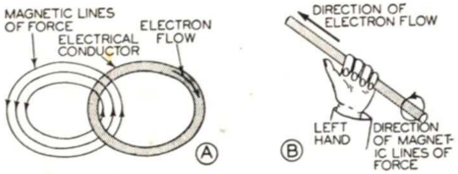


FIG. 1. Direction of magnetic lines of force around a conductor carrying a flow of electrons.

When the wire is moved from front to back at a speed of, say, one inch per second, the instrument will show that an electrical pressure (voltage) has been developed in a given direction along the conductor. When the motion of the wire is reversed (that is, moved from back to front between the pole faces), the instrument will read in the other direction, indicating that the direction of the e.m.f. induced in the conductor has been reversed. When the conductor is moved twice as fast, the instrument reading will double. When the conductor is moved five times as fast, the instrument will show that five times the original value of voltage is produced. When the length of the conductor exposed to the magnetic field is reduced by one-half and the conductor moved across the field at the original speed, the original induced voltage will be reduced to one-half.

When the density of the magnetic flux is made ten times that of the original value by substituting an electromagnet for the permanent magnet, and the conductor is moved across this field at the original speed (one inch per second), the voltage indicated by the instrument will be ten times that for the permanent magnet. When the wire is moved across this stronger field ten times as fast as at first, the induced voltage in the conductor will be one hundred times (10 × 10) the original value.

If these experiments are repeated with the magnet turned upside-down, so the south pole is above the north pole, the instrument readings will be the same in magnitude as for corresponding previous tests, but will be in opposite directions (reversed polarities).

If the experiments are repeated with three conductors connected in series, as in Fig. *2B*, the voltage indicated by the instrument will be three times the value originally obtained. The use of ten conductors in series will give ten times the voltage induced in a single conductor. If three, five or ten conductors are connected in parallel, however, there will be no increase in the total induced voltage in any case; here we would simply have the effect of one large wire equal in cross-section to the sum of the cross-sections of all of the parallel wires. The series connection is essential in order to obtain addition of the voltages induced in the individual conductors.

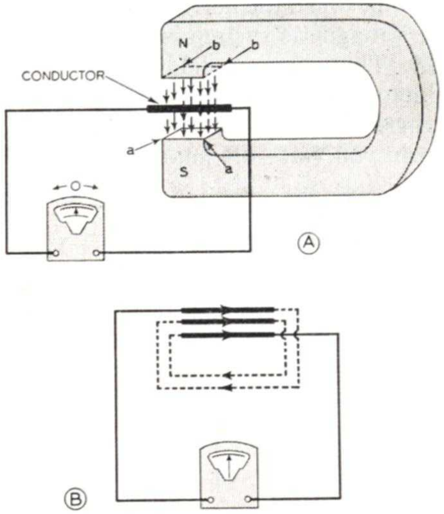


FIG. 2. Diagrams illustrating the law of induced voltage for a conductor which is moved across a magnetic field.

When one, three, five or ten conductors in series are moved diagonally across the field from rear edge *bb* of the north pole to front edge *aa* of the south pole at the original speed (one inch per second), the induced voltages are materially lower than for the corresponding cases where the lines of force were cut perpendicularly. When the conductors are moved parallel to the lines of force (from one pole straight up to the other), *no* voltage will be induced in the conductors.

The conclusions from all of the foregoing experiments may be summarized as follows: The voltage induced in a system of conductors moving in a magnetic field depends upon four factors: *1. The number of conductors in series; 2. The magnetic flux density* (the lines of force per unit cross-sectional area of the magnetic field); *3. The speed of the conductors perpendicular to the lines of force; 4. The length of the conductors in the magnetic field.*

This relationship between the induced voltage and the other factors may be unified into a very simple concept by referring to Fig. *3*, in which conductor *C* of length *L* (inches) is moved at a speed *S* (inches per second) across a magnetic field having flux density *B* (lines per square inch).

The runners on which the conductor moves are metallic and serve to complete the circuit to the voltmeter. In one second the conductor sweeps across the magnetic field a distance of S inches, and thus passes over an area in the magnetic field equal to L × S square inches. The strength of the magnetic field is *B* lines of force per square inch, hence the area covered has a total of B × L × S lines of force. Since we have shown that the induced e.m.f. depends upon the flux density, the length of the conductor and the speed of the conductor across the field, we can now see that the induced e.m.f. depends upon the *total number of lines of force cut per second.* If there are a number of conductors connected in series, each conductor will develop the same voltage and the voltages will add since the conductors are in series

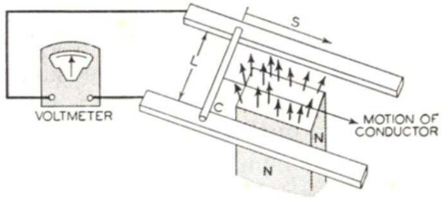


FIG. 3. The voltage induced in the moving conductor *C* in this simple circuit depends upon the total number of lines of force cut by the conductor per second, provided that this cutting changes the number of lines of force through the closed loop. The general rule is: The voltage induced in a closed loop moving in a magnetic field depends upon the ***rate of change of flux linkages*** through the loop.

Let us look at this induced-voltage relationship in a more technical manner. Think of the electrical circuit in Fig. *3* as a closed loop expanding in area due to the motion of the conductor. As the area of the loop increases, the loop links with more and more lines of force (the number of lines of force through the loop increases).

The value of the induced voltage depends upon how much change occurs (in a given unit of time) in the number of lines of magnetic force linking the loop or, as is often said, the induced voltage depends upon the *rate of change* of the lines linked by the loop. An example will clarify this; assume that at a given instant 1,000 lines of force pass through the loop, that one second later 2,000 lines link with the loop, and that two seconds later 3,500 lines link with the loop. The change in the flux lines linking the loop was 1,000 during the first second and 1,500 during the next second, and hence the *rate of change* of flux linkage was 1,000 per second during the first second and 1,500 per second during the next second. The induced voltage would be proportional to 1,000 during the first second and to 1,500 during the next second. If there were more than one turn in the loop, the *rate of change* of flux linkage would be the same for each turn, and each loop would have a voltage induced in it. The total induced e.m.f. would be the sum of these voltages.

When the number of flux linkages is *increasing*, the induced voltage has one direction. When the number of flux linkages is *decreasing*, the polarity of the induced e.m.f. is reversed. This latter case obviously corresponds to the case where the direction of motion of the conductor *C* of Fig. *3* is opposite to that shown in the illustration. Reversing the direction in which the flux passes through the coil without changing any other factors will reverse the polarity of the induced e.m.f.

Force on a Current-Carrying Conductor in a Magnetic Field

The third important relationship which we must consider deals with the magnitude and direction of the mechanical force exerted on a conductor which carries current and is located in a magnetic field. This can be explained quite simply with the aid of the diagrams in Fig. *4*. The uniform magnetic field between the north and south poles of a magnetic system is shown in Fig. *4A*. The magnetic field around a conductor is shown in Fig. *4B* for the case where the electrons are flowing away from you (into the paper).

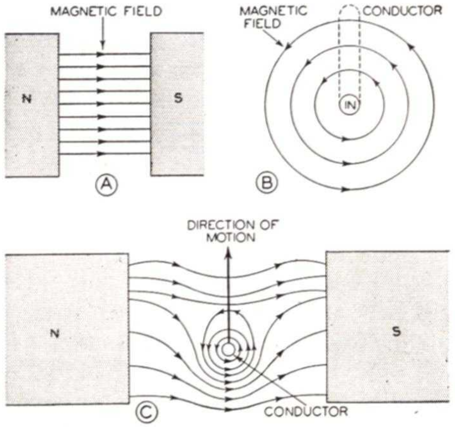


Fig. 4. Direction of motion of a current-carrying conductor in a magnetic field when electron flow through the conductor is away from you (into the paper).

Figure *4C* shows what happens when the conductor of Fig. *4B* is placed in the magnetic field of Fig. *4A*. The resultant magnetic field is obviously a composite of the two individual magnetic fields. Note that the lines of force under the conductor are compressed, because they are all in the same direction and *add*. Above the conductor, the two sets of lines of force are in opposite directions and subtract, causing a thinning of the flux.

We can visualize what happens if we imagine the lines of force to be hundreds of very thin rubber bands. Beneath the conductor they are depressed, and there is a strong urge for them to straighten out. This creates an upward mechanical force on the conductor. This upward force is actually on the field of the conductor (which cannot be separated from the wire) rather than on the conductor itself. Remember this important fact: When electrons are sent through a wire which is at right angles to magnetic lines of force, the *wire will be moved at right angles to both the direction of electron flow and the direction of the magnetic line of force.*

The force acting on a current-carrying conductor in a magnetic field will increase with increases in the magnetic flux density, in the length of the conductor exposed to the magnetic field and in the magnitude of the current flowing through the conductor; this is the fundamental principle of the electric motor. If the conductor rotates about a shaft, as is generally the case in the electric motor, the force on the conductor will exert on the shaft a rotating twist known as *mechanical torque*. The magnitude of the mechanical torque produced by an electric motor depends upon the force on the conductor and upon the distance of the conductor from the shaft.

Energy Laws for Generators and Motors

A more general consideration of the fundamental concepts involved in the operation of electrical generators and motors is now possible. Consider the case of the generator first. In Fig. *5A* suppose that the conductor is moved in direction *A* across the magnetic field; this, as we know, induces a voltage in the conductor. If we connect an external circuit having resistance *R* to the ends of the conductor, the induced voltage *E* will send an electron flow *I* through the conductor. The value of this current will be equal to the induced voltage divided by the circuit resistance ($I = E/R$).

The question is, what will be the directions of the induced voltage and of the current produced by this voltage? The answer is given by Lenz's law, which is derived from the natural law that energy can neither be created nor destroyed.

The voltage (*E*) which is induced in a conductor moving through a magnetic field will be in such a direction that the flux produced by the resulting circuit current (*I*) will tend to oppose the *change of flux linkages* which produced the induced voltage. Let us apply Lenz's law to the conditions set forth in Fig. *5A*. Since the motion of the conductor here is such as to decrease the flux linking the loop (decrease the flux linkages), the induced voltage in the conductor and the flow of electrons through it will be in such a direction that the flux produced by the resulting current will tend to increase the main flux inside the loop. The flux produced by the conductor will therefore have direction *C*. The direction* of the induced voltage and the direction of the electron flow will therefore be as shown by arrow *B*, in which the arrow points to the negative terminal of the conductor. (This can be verified by referring to Fig. *1B;* place your left hand over the conductor with your fingers pointing in direction *C*, and your thumb will then be pointing in direction *B*.)

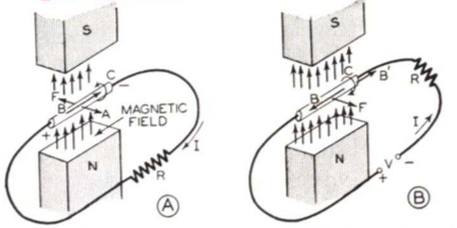


Fig. 5. These diagrams serve to illustrate Lenz's law, which tells the direction of the induced voltage in a dynamo-electric machine.

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*In this lesson, the "direction" of the induced voltage is the direction in which that voltage will force *electrons* through the circuit.

Now we have a conductor carrying current and moving in a magnetic field. The magnetic field of the conductor superimposed on the original magnetic field will cause a compression of the lines of force on the right of the conductor and a rarefication of the lines of force on the left of the conductor. There will thus be a mechanical force produced in the direction *F*, *opposing* the original motion of the conductor through the magnetic field. To keep the conductor moving, it is necessary to overcome this opposing force. This means that it is necessary to expend mechanical power in order to generate electrical power. This is the reason why Lenz's law for the direction of the induced e.m.f. was referred to as a special case of the law of conservation of energy.

As the load on a generator increases (as *I* increases due to reduction of *R*), the amount of power required to overcome the opposing force increases. Actually the mechanical power required to keep the conductor in Fig. *5A* moving is greater than the power needed to overcome this opposing force (and hence greater than the electrical power produced) by an amount necessary to overcome frictional and other losses.

Now consider the case of the motor. Referring to Fig. *5B*, assume that a voltage *V* is sending an electron flow through the conductor in direction *B*; the value of this current will be $I = V/R$ when the conductor is not moving. The magnetic field set up around the conductor by this current will be in direction *C* and will interact with the main magnetic field to produce a mechanical force acting on the conductor in direction *F*, which is *at right angles* to both the direction of electron flow and the direction of the magnetic lines of force. The conductor will start moving in this direction, thereby decreasing the number of lines of force threading the loop. According to Lenz's law, a voltage E_a will now be induced in the conductor, in such a direction as to tend to cause a current to flow which will increase the number of flux linkages. This voltage will obviously have the direction *B'*; it will therefore oppose the original electron flow *B*, and reduce the force on the conductor.

The induced voltage in the case of a motor is always opposite to the direction of the externally-applied voltage, and is therefore termed a *back e.m.f.* Because of this back e.m.f. E_a, the current flowing through the conductor in Fig. *5B* is reduced ($I = \frac{V - E_a}{R}$) and the force on the conductor is accordingly reduced. To maintain a given force on the conductor and hence a given mechanical torque at the shaft about which the conductor is rotating, the applied voltage *V* must be increased enough to give the required value of current. This is again a case of the conservation of power; to generate mechanical power, it is necessary to expend enough extra electrical power to make up for the losses in the machine.

The facts discussed in this section may be summarized as follows:

1. *Generator Action.* If a conductor is located in a magnetic field and is acted upon by a mechanical force in such a manner that the conductor is made to cut lines of force, the induced e.m.f. will have such a direction that the resulting current will react with the magnetic field so as to set up a mechanical force in opposition to the driving force. Mechanical energy is converted into electrical energy.

2. *Motor Action.* If a conductor is located in a magnetic field and is carrying a current provided by some source of electrical energy, the resulting force will tend to produce motion of the conductor in such a direction that the induced e.m.f. will oppose the original flow of the current. Electrical energy is converted into mechanical energy.

Generator and motor action are entirely reversible; a good generator may act as a motor, and vice versa.

Simple Single-Phase A.C. Generator

The elementary alternating-current generator shown in Fig. *6A* has two poles, *N* and *S*, produced by an electromagnet. A rheostat inserted in the field circuit serves to control the strength of the electromagnet. Between the field poles, a loop of wire called the *armature* is rotated mechanically about an axis. The armature is generally wound in an iron frame-work (not shown) which serves to reduce the reluctance* of the complete magnetic circuit and thereby increase the total flux. As the armature loop is rotated, a voltage is generated in a manner to be described later. Two slip ring-and-brush assemblies serve to transfer this voltage to the external circuit (to the terminals marked *A.C.*). The slip rings are generally of copper, while the brushes are made either of copper or carbon.

The magnitude of the voltage generated in the armature loop at each instant while it is being rotated may be considered in terms of the change in the flux threading the loop. Figure *6B* shows how the generated voltage varies during one complete revolution of the loop. At position *A* we have maximum flux linkage through the loop, but a small angular change in loop position produces only a negligible change in the flux linkage; the induced voltage at position *A* is therefore zero. This same condition exists after the loop has rotated through 180 degrees (position *E*) and through 360 degrees (position *I*, which is the same as position *A*).

At positions *C* and *G* the loop is parallel to the lines of flux, and the flux linkage is therefore zero. A small angular change in loop position produces a marked change in the flux linkages, however; the induced voltage is therefore a maximum at positions *C* and *G*.

The direction of the induced voltage at any position may be determined by applying Lenz's law. Consider position *H* in Fig. *6B*, which corresponds to the coil position shown in Fig. *6A*. Since the coil is rotating in the direction of increasing flux linkage, the flux produced around the conductors by the induced current must *oppose* the main field. The directions of the induced voltages in the conductors are then as shown by the arrows in Fig. *6A*. Note that the voltages induced in the two conductors of the armature loop are additive. Further increase in voltage may be obtained by increasing the number of turns in the loop winding, as shown in Fig. *6C*.

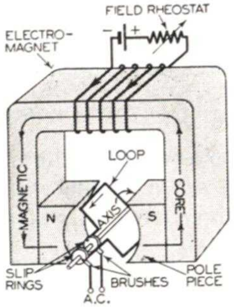

Fig. 6A. An a.c. generator in its simplest form has one coil of wire revolving in the magnetic field produced by an electromagnet.

It will be seen from Fig. *6B* that the induced voltage is alternating in nature, and passes through a complete cycle of variations during each revolution of the armature coil. Hence, to produce a frequency of 60 cycles per second (universally employed in U.S.), the armature of this simple a.c. generator must revolve 60 times per second or 3,600 times per minute (3,600 r.p.m.). It is possible to reduce this speed re-

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*The opposition which a magnetic circuit offers to the passage of a magnetic field is known as reluctance.

quirement by increasing the number of poles in the field structure. If four poles are used, with adjacent poles of opposite polarity, each revolution of the armature will produce two complete cycles of variation in the induced voltage. The speed for 60 cycles per second need now be only 30 revolutions per second or 1,800 r.p.m. In general, the relationship between the frequency f, the number of poles P and the revolutions per minute n may be expressed by the following simple formula:

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

For two poles and 3,600 r.p.m.:

$$f = \frac{2 \times 3{,}600}{120} = 60 \text{ cycles per sec.}$$

For four poles and 1,800 r.p.m.:

$$f = \frac{4 \times 1{,}800}{120} = 60 \text{ cycles per sec.}$$

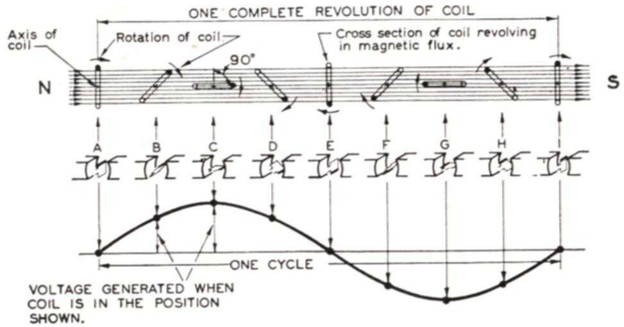


FIG. 6B. When a coil of wire is rotated at constant speed in a uniform magnetic field, the voltage generated will vary in the sine-wave manner shown here.

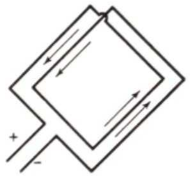


FIG. 6C. Two turns give twice the induced voltage.

It is important to know that the induced voltage of an a.c. generator which produces a given frequency is independent of the number of poles used. A consideration of the examples in the preceding paragraph will show why this is true. A two-pole a.c. generator sweeps a coil through the flux of one pole in half a revolution at the speed of 3,600 r.p.m., while a four-pole a.c. generator sweeps a coil through the flux of one pole in one-fourth of a revolution at a speed of 1,800 r.p.m. The coils on both machines thus cut through the flux of one entire pole in exactly the same time. The maximum rate of change of flux is therefore the same for a two-pole generator as for a four-pole generator, and the maximum induced voltages must likewise be the same. A similar analysis for other generators would show that the value of the induced voltage in a single loop of an a.c. generator is the same for a given frequency regardless of the number of pairs of poles employed. The number of armature turns and the strength of the magnetic field are obviously the important factors which control the magnitude of the induced voltage.

The field of a simple a.c. generator is generally excited from an external d.c. source, which may be a small d.c. generator called the exciter, employed especially for this purpose.

Most a.c. generators are multipolar. For power outputs up to 20 kilowatts, the field structure is generally stationary and the armature rotating. For greater generated powers, the following two factors make it more desirable for the field to be rotating and the armature to remain stationary: *1*. The current-handling requirements of the slip rings and brushes are very much reduced, as the exciting power required for the field is only a few per cent of the generated power; *2*. Higher voltages may be handled more readily by a stationary armature.

Figure 7 shows a single-phase alternator (a.c. generator) with a stationary armature and a six-pole revolving field. Note that the direct current for exciting the field is brought in on the slip rings. The stationary armature winding consists of a number of multi-turn coils connected in series. As a pole passes a coil, the flux associated with the pole sweeps through the coil, changing the flux linkages of the coil and thereby inducing in it a voltage. The connections to alternate coils are reversed, in order that the induced voltages will be additive when poles of opposite polarity pass them. For a 60-cycle frequency, a speed of 1,200 r.p.m. is required for the field structure.

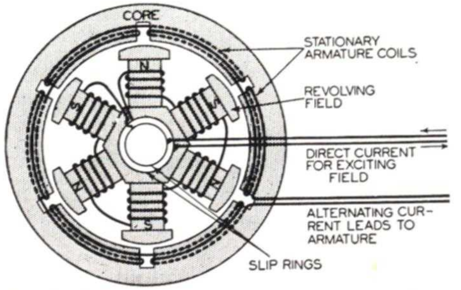


FIG. 7. Diagram of an a.c. generator having a 6-pole revolving field and a stationary armature.

A Simple D.C. Generator

Purpose of the Commutator. So far, we have considered only the production of alternating current by means of a generator. Dynamo-electric generators are also employed to produce direct or continuous currents. It must be understood, first of all, that the voltages set up in the various armature conductors of a generator are always alternating, no matter how the armature is wound. It is impossible to wind a generator armature in such a manner that direct current can be obtained from the terminals of the armature coil. It is necessary to employ some device which will always keep the direction of current flow in the external circuit in one direction, even though the current reverses in the armature coil or loop. This device, known as the *commutator* of a d.c. generator, *mechanically and periodically reverses the connections between the armature conductors and the load, so that the voltage applied to the load is always in the same direction.*

A simple d.c. generator is shown in Fig. *8A*. The two segments of the simple commutator are connected to opposite ends of the armature loop. The segments are made of copper and are rigidly fastened to the armature shaft by means of suitable insulating material. The operation of the commutator in converting a.c. into d.c may be understood by reference to Fig. *8B*. In this illustration, conductors *a* and *b*, which form the simple armature loop, are shown embedded in slots in the armature core. (As indicated previously, this core is used to lower the reluctance of the magnetic circuit.) The lead from conductor *a* of the armature loop is connected to armature segment *1*, and the lead from conductor *b* of the armature loop is connected to commutator segment *2*.

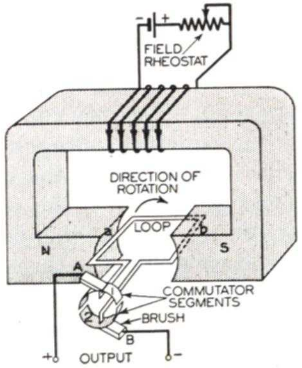


FIG. 8A. Simple d.c. generator.

When the armature loop in Fig. *8A* is rotated, voltages are induced in it exactly as in the case of the simple a.c. generator. The induced voltage is zero at positions *A*, *E* and *I*, and is a maximum at positions *C* and *G*, as indicated in Fig. *8B*. The polarity of the *induced* voltage at position *G* is the opposite of that of position *C*, as may be determined by applying Lenz's law. The voltage induced in the armature loop will therefore vary with armature position in the sine-wave manner represented by curve *A-C-E-G-I* in Fig. *8B*. As the armature approaches position *E* (where the induced voltage drops to zero), brushes *A* and *B* (which connect to the external circuit and which have been passing over segments *1* and *2* respectively) approach the opposite segments. At position *E* each brush contacts both segments. After position *E* has been passed, brush *A* contacts segment *2*, and brush *B* contacts segment *1*. Thus you can see that although the armature voltage reverses in polarity at position *E*, the connections of the armature to the external load are also reversed at this point, so that the voltage applied to the external load still has the same direction. This is the process of commutation. The variation of the voltage applied to the load is as shown by curve *A-C-E-*G_1*-I*, and is a pulsating direct voltage instead of the alternating voltage generated in the armature loop.

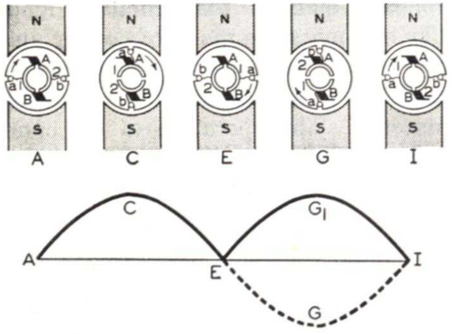


FIG. 8B. Output voltage curve for a simple d.c. generator.

It is important to note that at the instant of reversing the brush connections to the commutator, the armature loop is short-circuited by the brushes. This occurs at the point when the induced voltage is practically zero, however, so sparking at the commutator is minimized.

Armature Windings

The pulsating voltage (and current) delivered by the simple d.c. generator of Fig. *8A* is of little practical value. Commercial direct-current applications require much more uniform voltage and current. The manner in which this is accomplished will now be considered.

Referring to Fig. *8C*, let curve *1-3-5* represent the pulsating voltage delivered by the simple d.c. generator of Fig. *8A*. A second armature coil, placed at right angles to the first coil and operating in conjunction with a second commutator-and-brush assembly, would produce the pulsating voltage represented by curve *2-4-6* of Fig. *8C*. If we add together the voltages delivered by the two sets of commutators, the resultant or total e.m.f. will be represented by curve *E;* clearly there is much less fluctuation in amplitude in this voltage than in either of the component voltages.

In direct current generator practice, a large number of loops called *winding elements* are distributed around the armature and are connected in special sequence to arrange for even more complex addition of the component voltages, thereby insuring a practically uniform output voltage. The winding sequences employed are referred to as *lap* and *wave* windings. Winding elements for these two types of windings are shown respectively at Figs. *9A* and *9B*. The essential difference is that in the lap winding, opposite ends of a coil connect to *adjacent segments on the commutator,* while in the wave winding, opposite ends of a coil connect to *diametrically-opposite commutator segments.* Although only single-turn winding elements are shown in Figs. *9A* and *9B,* it is customary to use several turns per element, particularly when high voltages are required. In the next few paragraphs you will learn that the total generated d.c. voltage is affected by the number of turns per winding element and by the number of winding elements connected in series around the armature (between the positive and negative brushes).

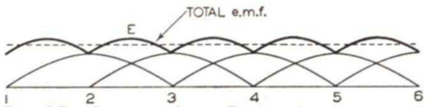


FIG. 8C. Output voltage *E* of a d.c. generator having two sets of commutators.

A photograph of typical multi-turn lap-wound coils appears in Fig. *10A*. The loops are made up in a jig, then fitted into slots in an armature of the type shown in Fig. *10B*. One coil fits into slots numbered *1* and *6,* with its leads connected to commutator segments *b* and *c;* another coil fits into slots numbered *3* and *8,* with its leads connected to commutator segments *c* and *d,* and so on around the armature.

Now let us consider the complete armature winding in Fig. *10B*. It is a lap-type winding for a two-pole d.c. generator. The small circles in the armature slots represent the conductors of the winding elements. The dotted lines from the commutator segments to the conductors represent the connections back of the armature, and these wires normally lie on a cylindrical face forming an extension of the armature core, but of somewhat smaller diameter. The solid lines represent the connections between conductors in front of the armature, and lie on a similar cylindrical surface forming an extension of the armature core at the rear. The small dots and crosses in the circles representing the conductors indicate the directions of the voltages induced in the conductors at the particular armature positions shown. A dot signifies that the induced voltage would tend to force electrons *out of* the conductor (toward you and away from the commutator), and the cross indicates an induced voltage which is forcing electrons into the conductor (away from you and toward the commutator). Figure *10B* is for the particular armature position shown; the induced voltages in any one conductor will naturally reverse in direction at each half-revolution of the armature in this case.

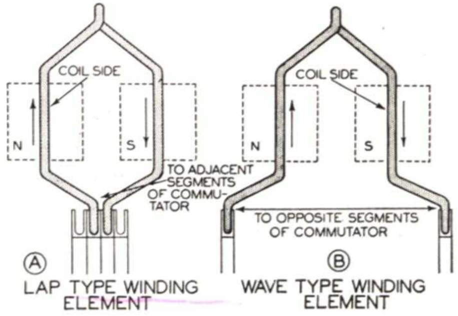


FIG. 9. Types of winding elements.

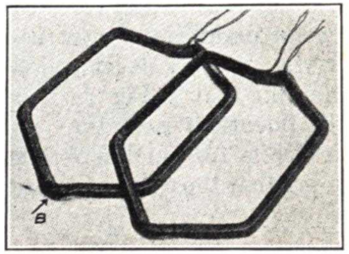


FIG. 10A. Typical multi-turn lap-wound coils. The special twist which allows the coils to fit close together is indicated at *B*.

Starting from brush *B,* let us trace the electron flow paths through the winding until brush *A* is reached. Note that there are two parallel paths, as follows:

Path *1:* From brush *A* to commutator segment *c,* into *6,* out of *6* and across to *1,* out of *1* to *b,* into *4,* out of *4* and across to *11,* out of *11* to *a,* into *2,* out of *2* and across to *9,* out of *9* to *f,* and then to brush *B*.

Path *2:* From brush *A* to commutator segment *c,* into the back end of conductor *3*, out of the front end of *3* and across to *8*, out of *8* to *d*, into *5*, out of *5* and across to *10*, out of *10* to *e*, into *7*, out of *7* and across to *12*, out of *12* to *f*, and then to brush *B*.

Since it is somewhat difficult to visualize complete paths from brush to brush in a cross-sectional picture diagram like that in Fig. *10B*, it is customary for designers of electrical machinery to employ a developed type of diagram like that in Fig. *10C*. This is for the identical armature winding shown in Fig. *10B*, and is obtained by imagining that the cylindrical surfaces of the armature, commutator, etc., are unrolled and placed on a flat surface with the poles underneath in the proper positions. The two poles and two brushes are considered to be fixed as to position, with the windings and the commutator segments sliding past them in the direction of rotation.

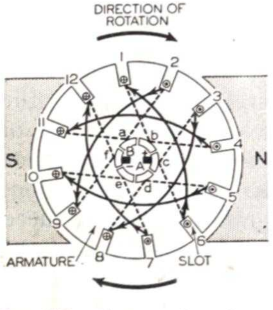


Fig. 10B. Cross-section view of simple two-pole d.c. generator, looking from the end *opposite the commutator. A* and *B* are brushes, while *a, b, c, d, e* and *f* are commutator segments.

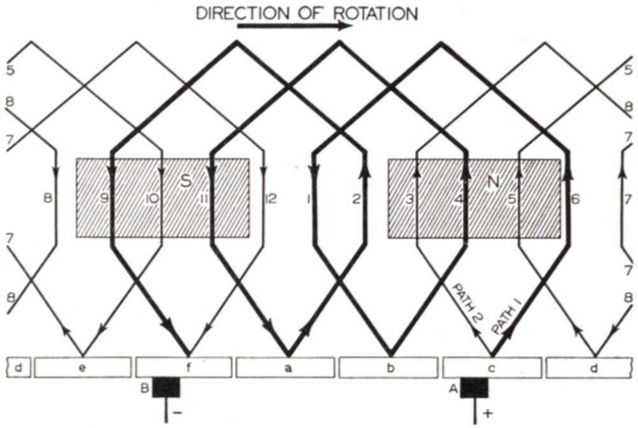


Fig. 10C. Developed diagram of a simple two-pole lap-wound d.c. generator. Arrows indicate directions of induced voltages (directions of electron flow) through the armature.

Let us trace the two electron flow paths between brushes *B* and *A* in Fig. *10C*, then figure out why the induced voltages have the directions shown.

Path *1* is easily traced now: *A* to *c* to *6* to *1* to *b* to *4* to *11* to *a* to *2* to *9* to *f* to *B*. Path *2* is: *A* to *3* to *8* to *d* to *5* to *10* to *e* to *7* to *12* to *f* to *B*. Note that there are three complete winding elements in each of the electron paths.

Consider first the winding element formed by conductors *1* and *6*; this is approaching maximum flux linkage in both Figs. *10B* and *10C*, and the induced voltage in this element is approaching zero since a small movement causes very little change in flux. Commutator segment *b* is approaching brush *A*; a slight additional rotation brings *b* to *A*, short-circuiting this winding element preparatory to reversing its connections to the brushes.

While winding element *1-6* of path *1* is approaching zero voltage, winding elements *4-11* and *2-9* are producing quite high induced voltages. Since these three winding elements are in series, and are connected in such a way that the voltage is in the same direction at all points along the circuit (you can verify these directions by applying Lenz's law), the voltage between the brushes will be the sum of the three different values of induced voltage. As the armature revolves, the voltages in the individual coils (winding elements) will vary in a sine-wave manner, but the sum of these three induced voltages will vary only a small amount. Path *2* is in parallel with path *1* between the brushes, and produces the same essentially-constant output voltage at the brushes. This gives very nearly a pure d.c. voltage; by placing more winding elements on the armature, an even steadier output d.c. voltage can be secured.

The voltage induced in a winding element reverses each time the sides of this element arrive at the neutral zones between poles. In a d.c. generator the connections to a winding element must, therefore, be reversed each time the element arrives at a neutral zone. The winding element must be short-circuited by a brush before its connections can be reversed, and consequently we must provide an adequate number of brushes, located at the proper points on the commutator, to accomplish this short-circuiting and reversal of connections.

Only two brushes are needed for two-pole d.c. generators, regardless of whether they employ a lap winding or a wave winding. By considering this brush problem now for a four-pole d.c. generator, we can arrive at important general conclusions which will apply to d.c. generators having any number of poles and employing either a lap winding or a wave winding.

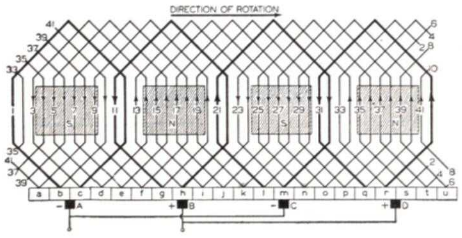


Fig. 11A. Developed lap winding.

The developed lap winding for a four-pole d.c. generator is shown in Fig. *11A*. The four winding elements, which are in or approaching the neutral zones between poles and must therefore be short-circuited by brushes when the armature is rotated a small amount in the direction of rotation, are shown in heavy lines. As you can see, brush *A* is already shorting commutator segments *b* and *c*, thereby short-circuiting the first of these winding elements (having conductors *1* and *12*). A small amount of additional rotation will bring commutator segment *g* in contact with brush *B*, short-circuiting the second winding element (having conductors *11* and *22*). Still further rotation will bring segments *l* and *m* in contact with brush *C*, shorting the third winding element (having conductors *21* and *32*). Finally, segments *q* and *r* will contact brush *D*, shorting the fourth winding element (having conductors *31* and *42*). We obviously cannot use less or more than four brushes for this four-pole lap-wound d.c. generator. Our general conclusion is that *with a lap winding we must have as many brushes as there are poles.*

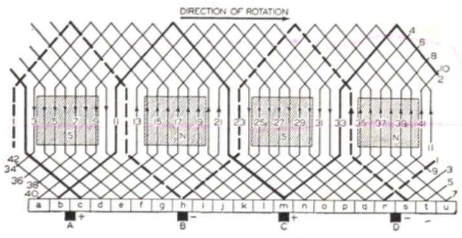


Fig. 11B. Developed wave winding.

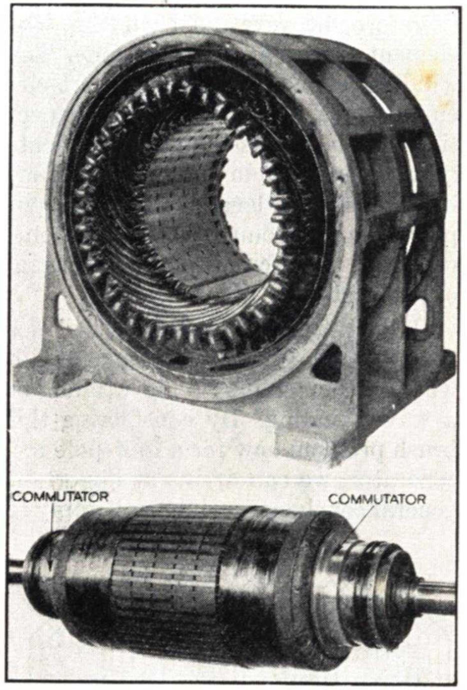
A developed wave winding for a four-pole d.c. generator is shown in Fig. *11B*. The winding elements which are in neutral zones and must therefore be short-circuited by brushes are shown here in heavier lines. A careful study of this diagram will show that brush *A* is shorting commutator segments *b* and *c*, and is therefore shorting two winding elements connected together in series, one having conductors *11* and *22*, and the other having conductors *33* and *2*. Brush *D* is short-circuiting the other two winding elements which are in neutral zones, for these are connected together in series between commutator segments *r* and *s* (one winding element has conductors *1* and *12*, and the other has conductors *23* and *34*). We thus have short-circuiting of four windings with only two brushes in the case of a wave winding. Brushes *B* and *C* may be used if individual short-circuiting of winding elements is desired; in this case, brush *C* would be connected to brush *A*, and brush *B* would be connected to brush *D*. Our general conclusion is that *only two brushes are required regardless of the number of poles in a wave-wound d.c. generator.*

A lap winding is often called a *parallel* winding, for a simple lap winding always has as many parallel paths through the armature between the output terminals as there are poles. A wave winding is often called a *series* winding, for a simple wave winding has only two parallel paths through the armature between generator terminals regardless of the number of poles.

The Effect of Armature Reaction on Commutation in a D.C. Generator

Figure *12A* shows the magnetic field produced by the field poles of a d.c. generator when the armature is stationary (no generated voltage). The field is symmetrical and practically uniform since the armature now acts only as a portion of the main magnetic circuit, with the armature core tending to reduce the reluctance of the complete system. When the armature of a d.c. generator is rotating, the electron flow through the conductors could be as shown in Fig. *12B* for the direction of rotation indicated. If we could remove the main magnetic field temporarily under this condition, the magnetic field produced by electron flow through the rotating armature windings would be as shown in Fig. *12B*. When both magnetic fields exist simultaneously, as they do in a d.c. generator, the armature flux naturally affects the field flux to some extent, depending upon the relative strengths of the two fields. The result of this reaction between the two fluxes is a redistribution of flux lines, as shown in Fig. *12C;* this effect is referred to as *armature reaction.*

Rotation of the armature in a generator seems to pull the field magnetism around with it, or to stretch it out of place *in the direction of rotation.* Because of this, the strongest part of the magnetic field is not where it was when the armature was stationary—it has moved to one side in the direction of rotation. This displacement naturally takes place equally at each field pole, and the amount of displacement is largely determined by the load.



Courtesy General Electric Co.

Field (stator) and armature (rotor) of a General Electric CY-98 d.c. generator capable of delivering 100 kilowatts of power at 15,000 volts d.c. The windings on the inside of the field structure are all compensating windings, fitting into slots in the faces of the two field poles. They completely hide the main field pole windings in this view. The armature has two sets of windings, each generating 7500 volts; the two commutators, one at each end of the armature, each serve one of these windings. In this way each brush handles only 7500 volts, reducing the tendency toward sparking. The two sets of brushes are connected in series externally to give the full 15,000 volts.

Mention has already been made of the fact that brushes must be so placed that they will short commutator segments whose conductors are in the zero field between poles. Now it is reasonable to believe that when the field is distorted or changed as just described, the amount of field distortion will have to be considered in setting the brushes. According, the brushes in a d.c. generator should be moved away from the dead-center position* *in the direction of armature rotation* to minimize sparking at the brushes. The distance from dead center is determined by the amount of field distortion.

In practice, brushes are actually set even farther in the direction of rotation, so that a small voltage of the same polarity which the neutral coil is about to have induced in it is set up in the coil. This small voltage operates to overcome the effect of self-inductance in the coil; this self-inductance tends to maintain in the coil during short-circuit a current having the same direction as that flowing in the coil prior to short-circuit. Advancing the brushes slightly beyond the true neutral thus tends to prevent sparking at the brushes.

Reentrancy of Windings

In all of the windings treated so far, if we started with conductor *1* and traced through the windings (regardless of the direction of induced voltage) we would pass through *all* the conductors before reaching conductor *1* again. These windings are known as *single-reentrant windings*. It is possible to arrange the windings so that they are double-reentrant, triple-reentrant, etc. Double-reentrant windings are obtained by sandwiching two windings of the same kind (lap or wave) on a single armature. Each winding has its own commutator segment, the two sets of segments being interleaved. The brushes must be of sufficient width (at least twice the width of a commutator segment) to provide for short-circuiting of a winding element in each winding at the neutral zones. If we started with conductor *1* and traced through the winding, we would pass through only half the conductors before reaching conductor *1* again.

Triple-reentrant windings are obtained by sandwiching three windings of the same kind on a single armature and interleaving three corresponding sets of commutator segments. The brushes must now be at least triple width.

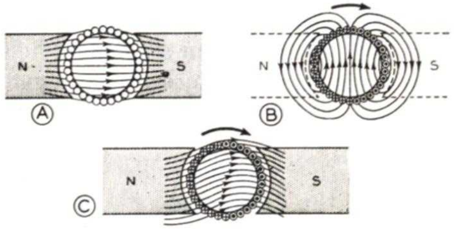


Fig. 12. Distortion of the main magnetic field due to armature reaction.

Winding Pitch and Commutator Pitch

The *winding pitch* is the number of sides of winding elements which are passed over in connecting one conductor to another on the armature. *Front pitch* refers to the connections at the front or commutator end of the armature winding, and *back pitch* refers to the connections at the back end. In Fig. *11A*, conductor *1* connects to conductor *12* at the rear, and hence the back pitch is +11; conductor *12* connects to conductor *3* at the front, and hence the front pitch is —9. (The conductor to which a connection is made is always counted when determining pitch.) The signs refer to the direction of progression of the winding around

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***The "dead center" position of a brush is the position it would be placed at if there were no distortion of the field flux by armature reaction.**

the armature. A + sign indicates progress in the direction of rotation, while a — sign means progress opposite to the direction of rotation. Since this is a lap winding, the winding laps back over itself and there is a negative progression at the front end. In Fig. *11B*, a wave winding, both the front and back pitch are +11.

The *commutator pitch* refers numerically to the spacing of the commutator segments to which the two terminals of a winding element are connected. In Fig. *11A* the commutator pitch is +1, in Fig. *11B* it is +11.

Armature Windings for Single-Phase A.C. Generators

In Fig. *7* was shown a rotating field and stationary armature of an a.c. generator. The type of winding shown on the armature is known as the *chain* type. The lap winding is also generally used for the armatures of a.c. generators (whether of the rotating-field or rotating-armature types). The stationary armature (rotating-field type) requires slip rings only for the field connections.

When a lap winding is employed on a stationary armature, the various winding elements are connected together in series in such a way that voltages will all be in the same direction at any instant of time. Voltages induced in adjacent coils will be out of phase, for when flux is changing at a maximum rate for one coil it will be changing at a lesser rate for adjacent coils. The voltages induced in the various coils are sine-wave in form but differ in phase, so they all add up to produce a sine-wave output voltage at the generator terminals.

Field Excitation for A.C. and D.C. Generators

As has already been mentioned, a direct current is required for field excitation of any generator. A.C. generators therefore require a separate d.c. source, usually a small d.c. machine called an exciter. A small a.c. generator can be made self-excited by employing a commutator on the rotating armature shaft to rectify part of the a.c. output for field excitation. D.C. generators, on the other hand, may be operated self-excited; since the armature supplies direct current, part of this current may be used to excite the field. As will be shown, all or part of the field coils may be in parallel or in series with the load, depending on the operating characteristics desired for the generator.

Operating Characteristics of the Single-Phase A.C. Generator

The factors defining the operating characteristics of a generator are: armature speed (S), induced armature voltage (E_a), armature current (I_a), field current (I_f), the terminal voltage applied to the external load (V_t), and load current (I_L). We have shown that for a constant output frequency, the voltage generated in a single-phase a.c. generator will vary directly with the strength of the magnetic field.

The terminal voltage (V_t) will be less than the generated voltage (E_a) by a voltage drop in the armature (I_aZ_S, where Z_S is the impedance of the generator during operating conditions). This voltage drop is caused by the flow of current through an armature winding having both resistance and reactance. The resistance is the ohmic resistance of the winding. The reactance is the sum of the inductive (or self) reactance of the armature and a fictitious reactance which takes into account the effect of armature reaction. The term "Z_S" is called the *synchronous impedance* and includes both the resistance and the total reactance of the armature.

Assuming that the armature speed remains constant, the *induced* voltage will remain constant regardless of the load current. However, the voltage drop in the armature will increase as the load current increases, since I_L and I_a are identical (a series circuit). The terminal voltage V_t (equal to $E_a - I_aZ_S$) will therefore decrease as the load current increases.

The term *voltage regulation* (expressed in per cent) is often used as a figure-of-merit of a generator. It defines *the per cent drop in terminal voltage when changing from no-load to full-load conditions.*

The terminal voltage of an a.c. generator may be kept constant by increasing the field current (and hence the flux) as the load current increases. In this way E_a is increased just sufficiently to make up for the increased voltage drop in the armature as load current increases. This may be done manually by means of a field rheostat, or automatically by means of relays which are operated by the load current and serve to control the amount of resistance in the field circuit.

Figure *13* shows how the induced voltage of an a.c. generator varies with the current flowing through the field windings. During normal operation the field current is set on an essentially linear portion of the curve, close to the point of magnetic saturation, so that an increase or decrease in field current causes a corresponding variation in the induced voltage. At zero field current, there is still some residual magnetism in the field magnets, hence the induced voltage does not drop down to zero. Near maximum field current, the magnetic flux, and hence the induced voltage) does not increase linearly with the field current because of magnetic saturation of the field structure.

Operating Characteristics of the D.C. Generator

The induced voltage (E_a) of a d.c. generator has been shown to vary directly with the number of winding elements per path in the armature, with the flux per pole, with the number of pairs of poles, and with the armature speed. Since the d.c. generator is self-excited, variations in load current will cause variations in the field current and thereby affect the strength of the field flux. This in turn will affect the terminal voltage of the generator.

Figure *14A* shows the electrical connections for what is known as a shunt generator. For convenience the armature is represented by the commutator and brush assembly (since the brushes form the external connections to the armature), and a coil is used to represent the field. windings. Note that the field is connected in parallel (shunt) with the load, hence the name "shunt generator." It will be obvious that for this connection the armature current will be equal to the sum of the load current and the field current ($I_a = I_L + I_f$). The terminal voltage in this case will be the induced voltage minus the voltage drop in the resistance of

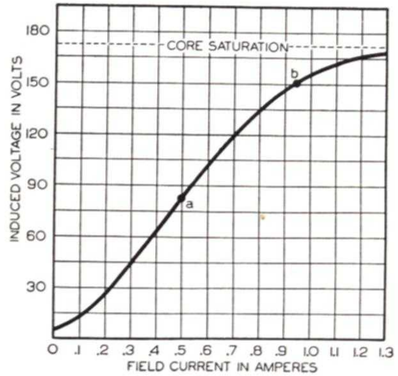


FIG. 13. Characteristic curve of an a.c. generator. Up to point *a* on the curve, increases in field current produce proportional increases in magnetic field strength and in induced voltage; above point *a*, magnetic saturation of the iron pole pieces and the armature core begins, so that given increases in field current produce less and less increase in the induced voltage. The saturation effect is not serious up to about point *b*, hence the region between *a* and *b* is usually selected as the operating range for field current. Complete saturation exists when the iron structure cannot hold any more magnetic lines of force; under this condition, additional increases in field current cause no further increases in magnetic field strength or induced voltage, and we are getting the maximum possible induced voltage (the value corresponding to the dotted line labeled *CORE SATURATION*).

the armature winding ($V_t = E_a - I_aR_a$). The terminal voltage will decrease somewhat as load current increases, first because of the increased I_aR_a drop in the armature and secondly because this reduction in terminal voltage in turn causes a reduction in field current and hence in the generated voltage E_a. The variation of the terminal voltage with load current for this type of machine is shown by curve *a* in Fig. *14D*.

Figure *14B* shows the electrical connections for a series generator. The field winding is connected in series with the armature, hence the name "series generator." This type of generator has very little application in modern practice. Since the field current is equal to the load current, it is apparent that the induced voltage will vary widely with the load current. Figure *13* expresses the nature of this variation, showing that in a series generator the induced voltage increases with load current. The terminal voltage will be less than the induced voltage by the IR drops in the armature and the series field.

We thus see that it is possible to have the terminal voltage decrease as load is applied (the shunt generator), or increase as load is applied (the series generator). By combining shunt and series field coils and providing the correct relationship between the strengths of these fields, it is possible to obtain a practically *flat voltage characteristic, so there will be negligible variation in the terminal voltage as load is varied.* A machine employing this combination of field windings is called a *compound generator*. The electrical connections of a compound generator as shown in Fig. *14C*, and the manner in which the terminal voltage varies with load current is portrayed by curve *b* in Fig. *14D*. By adjusting the relative strengths of the two field windings it is possible to make the voltage rise somewhat with load (*the over-compounded generator*) or drop slightly with load (*the under-compounded generator*).

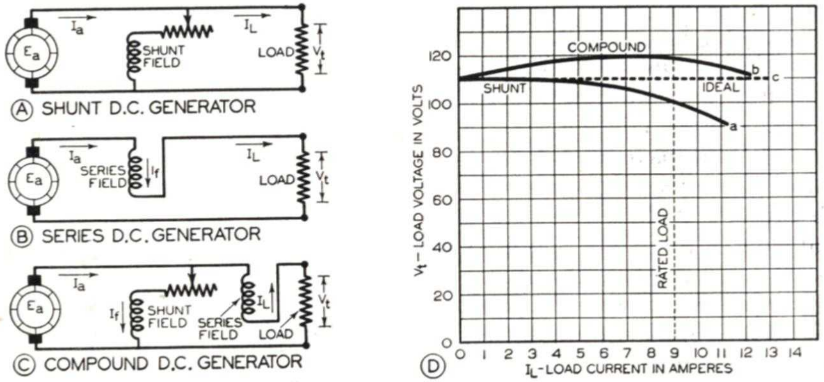
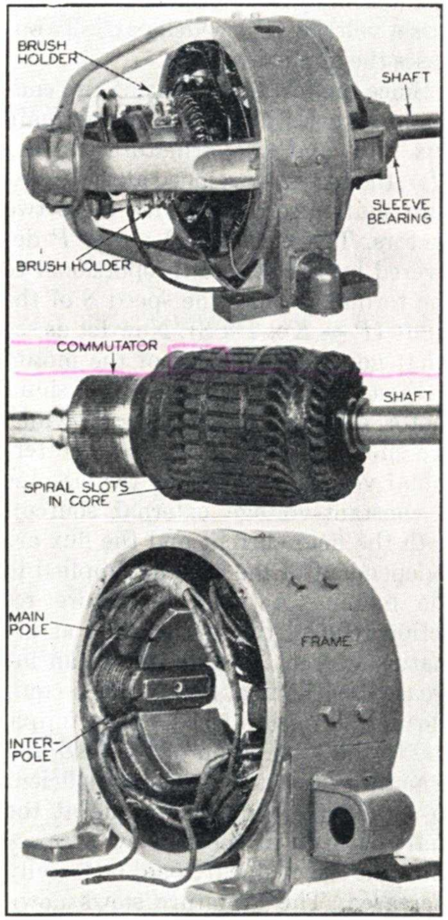


Fig. 14. Field connections for shunt, series and compound d.c. generators, together with output voltage—output current characteristic curves for shunt and compound d.c. generators.

It is of interest to consider how self-excited shunt or compound generators build up their generated voltages. When the armature is first rotated, the only induced voltage is that due to the residual magnetism of the field structure. Assuming no-load conditions, this small voltage will send a small current through the shunt field. If the armature is revolving in the proper direction, the polarity of the induced voltage will be such that the field due to this small field current will assist the residual field. The induced armature voltage is thus further increased, and it in turn increases the field current and the total field again. This process continues until the I_fR_f drop in the field coils is equal to the generated voltage E_a; we then have steady-state conditions, and the generated voltage will remain constant at this value until the field resistance R_f or the speed is changed.

The same building-up phenomena occurs in a series generator, but only when a load is applied. A series generator will not build up its magnetism under no-load conditions, for current cannot flow through the field coil until a load is connected to the generator.



Courtesy General Electric Co.

Top: This type CD General Electric four-pole d.c. motor, available with either shunt or compound-wound field coils, is typical of general-purpose d.c. motors larger than 3 h.p. in size. Center: Armature of the above motor. Bottom: Field structure of a type B General Electric d.c. motor, available in sizes from ½ h.p. at 1750 r.p.m. up to 10 h.p. at 3500 r.p.m. There are four main poles, and two interpoles to improve commutation.

Efficiency of Generators

The efficiency of a generator is equal to the ratio of the electrical power developed to the mechanical power supplied to it, expressed in per cent. For a self-excited generator, the mechanical power input must equal the electrical power output plus the resistance (I^2R) losses in the field and armature windings, plus eddy current and hysteresis losses in the armature core, plus frictional and windage losses. For example, if a generator delivers 10 amperes at 100 volts (1,000 watts) and the sum of all its losses is 100 watts, the mechanical power delivered to it will be the mechanical equivalent of 1,100 watts. The generator efficiency is 1000 ÷ 1100, which is 0.909 or 90.9%.

The D.C. Motor

The d.c. motor is essentially a d.c. generator to which electrical power is supplied, causing it to rotate and to deliver mechanical power at its shaft. The principle underlying motor action was explained in connection with Fig. *4*. The generation of a back e.m.f. as the armature rotates in the magnetic field was demonstrated in the text associated with Fig. *5B*. While these explanations were for a single conductor carrying current in a magnetic field, it is evident that they are applicable to armatures of the types described in connection with Figs. *10* and *11*.

Consider the lap-wound armature shown in Fig. *10C* (reproduced as Fig. *15* for convenience). Assume that an external voltage (V_t) is applied between brushes *A* and *B*. Let the polarity of the brushes be kept the same as they were when the machine was a generator, so that the positive lead is connected to *A* and the negative lead to *B*. Electron flow through the armature winding will then be in the directions indicated by the arrows at the right of the conductors. The magnetic lines of force produced by these electron flows will be in the directions indicated by the curved arrows under the conductors. It will be seen that for conductors over the face of the south pole (where the main field is away from you), the field set up by the current in the conductors opposes the main field at the right of the conductors and strengthens the main field at the left of the conductors; the result is a force tending to pull these conductors to the right. For conductors over the face of the north pole (where the main field is out of the paper, towards you), exactly the same conditions apply. The main field thus exerts a force on each armature conductor in the same direction, moving the armature to the right. The total force which tends to rotate the armature about the shaft is equal to the sum of the forces on the individual conductors.

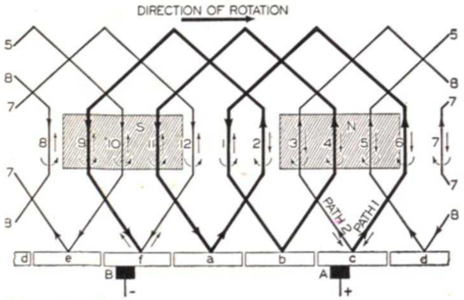


FIG. 15. Developed diagram of a simple lap-wound d.c. motor. Arrows alongside wires indicate direction of electron flow. Arrows on wires indicate direction of induced voltage (back e.m.f.). Curved arrows under conductors indicate directions of magnetic lines of force produced by the conductors.

Armature Current in a D.C. Motor. With the armature rotating in the direction shown, there is induced in each of the conductors a voltage which, in the absence of an externally-applied voltage, would tend to force electrons in the directions shown by the arrows on the conductors. The induced voltages oppose the externally-applied voltage, and the armature current is therefore equal to the difference between the two voltages divided by the ohmic resistance of the armature $(I_a = \frac{V_t - E_a}{R_a})$. Note that for a motor the terminal voltage is greater than the induced voltage, whereas for a generator it is less than the induced voltage. The armature current in a d.c. motor is a maximum value at the instant of starting (when E_a is zero). Armature current decreases as a d.c. motor comes up to operating speed, because rotation of the armature induces in its conductors a voltage (E_a) which partially opposes the applied voltage.

Since the force on the armature conductors varies directly with the main flux (Φ) and the armature current (I_a), the torque developed at the armature shaft also varies with these two factors. The mechanical power P delivered by the shaft is proportional to the torque T times the speed S of the shaft ($P = K \times T \times S$). Now let us see what governs the speed of the motor.

First we will consider the shunt motor, electrical connections for which are shown in Fig. *16A*. Since the terminal voltage is constant (we assume a constant-voltage external source), both the field current and the flux are independent of the current supplied to the motor. (Actually, armature reaction reduces the flux slightly as armature current goes up due to an increased mechanical load.) When equilibrium is established, the torque due to the interaction of the field and armature currents will be just sufficient to supply the required torque at the shaft at a given speed. Now suppose that the mechanical load is heavily increased. The armature slows down somewhat and (since Φ remains essentially constant) the induced voltage E_a is reduced. The difference between V_t and E_a increases, allowing a greater flow of armature current, and this in turn increases the torque. A new speed is finally reached, at which the torque is again sufficient to handle the mechanical load.

Actually, the armature speed change required to handle the complete range of load conditions from no-load to full-load is quite small, since a small change in the difference voltage ($V_t - E_a$), caused by a small change in induced voltage E_a, results in a large change in the current through the low-resistance armature windings. The shunt d.c. motor is usually considered a constant-speed machine.

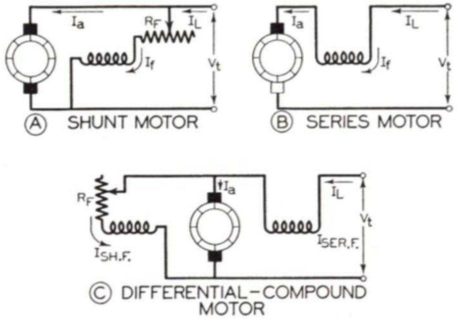


FIG. 16. Electrical circuits for three types of d.c. motors.

Suppose now that it is desired to increase the speed of rotation. Field rheostat R_F is adjusted to reduce I_f and hence Φ. E_a now decreases and I_a increases. The torque increases and the machine speeds up. A new speed is finally attained at which the torque due to armature current I_a

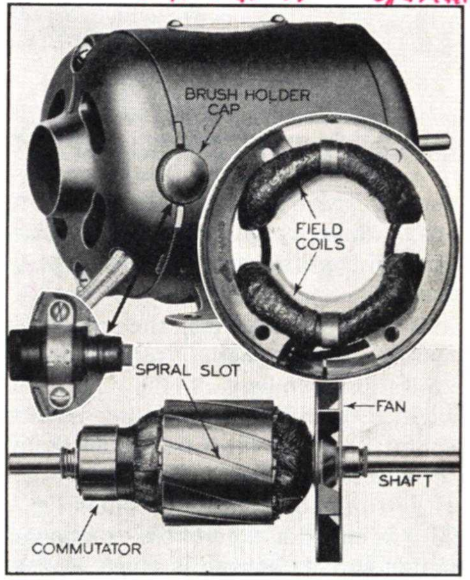
$$(I_a = \frac{V_t - E_a}{R_a})$$

is just sufficient to handle the mechanical load. It is obvious that, other conditions being fixed, the speed of a shunt motor increases as the field current is decreased, and vice versa.

Next consider the case of the series motor, the electrical circuit for which is given in Fig. *16B*. Since the field and armature currents are identical, an increase in the mechanical load is accompanied by an increase in both the armature current and the strength of the magnetic field. To reduce the induced voltage (in order to accommodate the increased armature current), the speed of the armature must decrease very much more than if the field strength had remained constant. For this reason the series motor is essentially a variable speed machine, with the speed decreasing as the mechanical load is increased.

If by accident, the strength of the magnetic field of a d.c. motor should be materially reduced (by opening the field circuit of a shunt motor, or by shorting turns in the field coils of a series motor), the armature speed will increase unduly in an attempt to generate sufficient back e.m.f. (E_a) to

same action as speeding up a shunt motor



Courtesy General Electric Co.

General Electric type P fractional-horsepower series motor for universal a.c.-d.c. operation. Both the field core and the armature core are made of high-quality laminated steel. The two brushes, on opposite sides of the armature, are connected in series with the two field poles. A fan at one end of the armature cools the motor by blowing air through ducts around the windings. Note that the laminations on the armature are stacked to give spiral slots; this construction tends to smooth out minor fluctuations in motor speed. These motors are also made with straight slots, which give better commutation (less sparking at the brushes) and more torque, but have a slightly fluttering speed characteristic. Universal series motors are used chiefly for high-speed applications where the load is directly connected and duty is intermittent, such as in small fans and blowers and in portable electric appliances. The speed of a series motor decreases rapidly as load is applied, so that full-load speed is only about 60% of no-load speed.

limit I_a to the value required by the mechanical load. This means that if the field circuit of a shunt-excited d.c. motor is opened while the motor is driving a very small load, the speed will increase rapidly until centrifugal force tears apart the armature and wrecks the motor; in engineering slang, the motor will "run away." This is also the case for the series motor when started under no-load conditions. The armature current requirement is then small, so that the field current (and flux) is accordingly low; the speed will increase to a very high value as already explained. Series motors are usually geared to their loads (as in street railway applications), so that no-load starting may not accidentally occur.

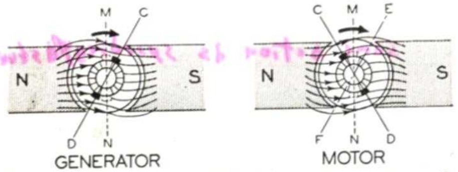


FIG. 17. Brushes are shifted from the center position *MN* in the manners shown here to compensate for armature reaction in d.c. generators and motors.

If it is desired to keep the speed of a motor constant within quite narrow limits independent of the load, the slight drop in speed with load may be compensated for in a shunt motor by the addition of a series field connection so as to oppose the main shunt field. This is called a *differential-compound motor* and its circuit is given in Fig. *16C*. The flux produced by the series field coil increases with load, thereby decreasing the main field. E_a is thereby reduced sufficiently to accommodate the increased armature current without a reduction in armature speed.

The direction of rotation of any series d.c. motor, shunt d.c. motor or universal a.c.-d.c. motor may be reversed by reversing the direction of electron flow through the armature winding, or by reversing the polarity of the field. If both are reversed, such as by reversing the polarity of the applied voltage, the direction of rotation will not change. These facts can be verified by referring to Fig. *15*.

Commutation in D.C. Motors

The subjects of armature reaction and of means for obtaining proper commutation are equally as important for motors as for generators. You will recall that in a generator the armature pulls the field along with it to a certain extent; in other words, the armature distorts the field. In a motor this distortion is in the opposite direction; the armature pushes the field backwards, if we consider the armature as moving forward. Adjustment to compensate for this field distortion (armature reaction) is made by shifting the brushes to points where no sparking occurs. Figure *17* shows the difference between generator and motor armature reaction, and how brushes are set to compensate for it in each case. Generator brushes are shifted from the center in the direction of rotation until no sparking occurs; motor brushes are shifted opposite to the direction of rotation until there is no sparking.

Most motors are designed to operate in only one direction. In this case brush setting is a comparatively simple matter. But it is not so easy to solve the problem of brush position in a reversible d.c. motor. It is physically impractical to reset the brushes each time the motor is reversed, and consequently the brushes of reversible motors are set at their neutral positions, and means are provided for proper commutation.

By placing in the faces of the field poles a number of conductors equal to the number of conductors on the armature and connecting these field pole conductors in series with the armature, we can produce an extra magnetic field which is equal in strength to the magnetic field created by the armature conductors. By making proper connections to the field pole conductors (known as *compensating windings*), the two magnetic fields can be made to oppose and cancel each other. The result is uniform distribution of the main field flux regardless of the direction of armature rotation.

In order to secure proper commutation in a reversible d.c. motor, some means must be provided for counteracting the self-inductance of the armature conductors. The brushes must be kept just midway between the poles, and cannot be shifted to accomplish this purpose, so reversible d.c. motors generally have small *interpoles,* located between the main poles. The small magnetic fields produced by these interpoles induce currents in the conductors which, at the instant of commutation, oppose the currents due to the self-inductance of the armature winding. Current in each coil is thus forced to zero the instant before that coil is shorted by a brush, and sparking is eliminated. The interpole windings are connected in series with the armature.

In small reversible motors, the compensating windings are sometimes omitted and the interpoles are relied upon for proper commutation and the elimination of sparking. Because they are in series with the armature, armature reaction is taken care of automatically and this self-adjustment varies with the load. Figures *18A* and *18B* show the positions of compensating windings and the interpoles. It will be seen from Fig. *18B* that the interpole is of such polarity as to extend the influence of that main pole which the armature conductor is just leaving. The voltage induced in the short-circuited coil thus has the same polarity as if the brushes had been set backwards. When the direction of rotation of the motor is reversed (by reversing the armature current), the polarity of the interpoles is also reversed, so that again their effect is equivalent to setting the brushes back from the neutral zones.

Efficiency of Motors

The efficiency of a motor is equal to the ratio of the mechanical power developed to the electrical power supplied to it from the line. The mechanical power is expressed in horsepower (abbreviated h.p.; 1 h.p. = 746 watts). The electrical power input is expressed in kilowatts (abbreviated kw.; 1 kw. = 1,000 watts). Part of the electrical power is used up in the I^2R losses in the field and armature windings, in hysteresis and eddy current losses in the armature core, and part of the mechanical power developed is used up in frictional and windage losses; only the remainder is available as useful mechanical power output. If the input power is 1,100 watts, of which 100 watts goes for losses, the power available for mechanical work is 1,000 watts or 1.34 h.p. The efficiency is

$$\frac{1,000}{1,100} = 0.909 = 90.9\%.$$

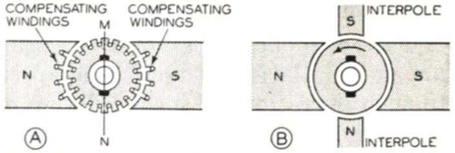


FIG. 18. Locations of compensating windings and interpoles in reversible d.c. motors.

The A.C. Single-Phase Motor

A.C. Operation of a Series D.C. Motor. In the study of the d.c. motor, it was shown that if both the polarity of the field and the direction of the armature current were reversed, the direction of rotation of the motor would remain the same. This means that if an a.c. voltage is applied to the terminals of a series d.c. motor, as indicated in Fig. *19*, it will still operate. Each time the voltage (and hence the line current) reverses, both the field and the armature current will reverse, and the armature will continue to rotate in the same direction. Such operation is not very efficient, however, because of high hysteresis and eddy current losses in the massive magnetic system due to the flow of alternating current through the field winding.

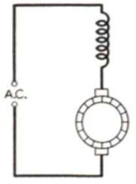


FIG. 19. A.C. series motor.

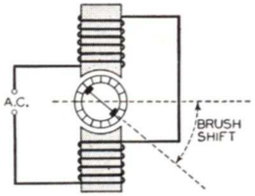


FIG. 20. A.C. repulsion motor.

In industrial applications where it is desired to operate a motor on either a.c. or d.c., the series motor is adapted to such operation by special design of the magnetic system to reduce losses. The armature core and component parts of the field structure are built up of thin sheets (laminations), the natural oxide coatings of which reduce eddy currents to a minimum. The universal motors used for driving remote controls on radio receivers, vacuum cleaners, fans, winding machines, etc., are often of the series type.

The A.C. Repulsion Motor. Suppose that the armature of an ordinary d.c. motor is placed between an a.c.-excited field structure, as shown in Fig. *20.* Let the armature brushes be short-circuited and be advanced beyond the neutral zone by 10 to 20 degrees. At each half-cycle of the applied a.c., the polarity of the field poles reverses, causing a reversal in the magnetic flux through the armature. The changing flux through the short-circuited armature coil induces in this coil a current which sets up its own field practically along the axis of the brushes. This field interacts with the main field to produce rotation of the armature. When the main field reverses, the induced current in the armature reverses, so that the direction of rotation of the armature remains the same. This is an *a.c. repulsion motor.* This type of motor is used extensively for low-power applications, because of its appreciable starting torque.

The Simplified A.C. Generator as a Synchronous Motor. Now assume that an a.c. voltage is applied to the stationary armature winding of a two-pole rotating-field type a.c. generator, as indicated in Fig. *21.* The rotating field is still supplied with direct current through slip rings, just as in the a.c. generator. The current through the stationary armature winding reverses every half-cycle, and consequently the polarity of armature poles *X* and *Y* reverses every half-cycle. At one instant, *X* will be north and *Y* south; a half-cycle later, *X* will be south and *Y* north, so *X* and *Y* are called a.c. poles. Consider a moment when *X* is south; it will then attract the north field pole, while *Y* (being north) will attract the south field pole. With the field in the position shown, it will rotate in a counter-clockwise direction until it lines up in the position *AA′*. Now assume that *X* and *Y* reverse polarity. Nothing will happen. The field structure is in a dead-center position and cannot be rotated by changes in the polarity of *X* and *Y*.

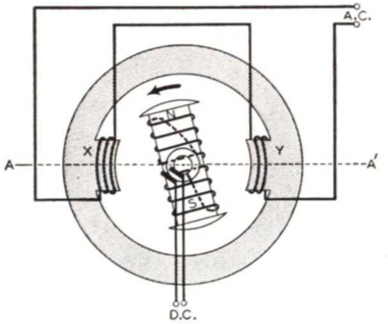


FIG. 21. A simplified a.c. synchronous motor.

Assume, however, that somehow the field structure is brought up to such speed that it travels just beyond the dead-center position *AA′* by the time *X* and *Y* reverse their polarity. The a.c. poles now repel the field structure, keeping it rotating in the original direction. Assume, further, that the rotor speed is just right so that (after another half-revolution) *S* will be just beyond *X* (and *N* will be just beyond *Y*) when the a.c. poles reverse again. *X* is now south and *Y* north, and the force of repulsion continues to keep the rotor (field poles) turning in the original direction. The rotor speed necessary to make this action continuous is called the *synchronous speed.* Once the rotor is brought up to this speed (say by an external drive), the latter drive may be disconnected, since the mechanical inertia of the rotor will then carry it over the dead spot *AA′* at each half-revolution. This is the principle of the synchronous motor.

It is not always convenient to start the motor up externally. Other means must be sought. For small synchronous motors of the type used in electric clocks, turntable drives, etc., manual spinning of the rotor to carry it over the dead spot is sometimes sufficient. In motors of the type to be described in the next section, a long, quick pull of a cord coiled tightly about the shaft serves the same purpose. Larger motors require other treatment, which will be discussed in following sections.

Minimum-Reluctance Type Synchronous Motor. An interesting development of single-phase synchronous motors, particularly adaptable to use where very small mechanical power is required, is shown in Fig. *22A.* The four-pole rotating system is nothing more than an annealed-steel rotor without windings, mounted on a shaft. This motor operates on the principle of minimum magnetic reluctance. The rotor poles tend to take positions which will make the reluctance of the field magnet structure a minimum, and consequently the rotor poles tend to line up with the field poles.

With alternating current flowing through the field pole windings, the strength of a field pole increases from zero to a maximum and drops down to zero again once for each half-cycle. If field current is increasing at the instant when the rotor is in the position shown in Fig. *22A*, the gradually increasing flux at field pole *M* will produce a gradually increasing force tending to bring rotor pole *W* in front of field pole *M*; at the same time, pole *Y* will be pulled toward field pole *N*.

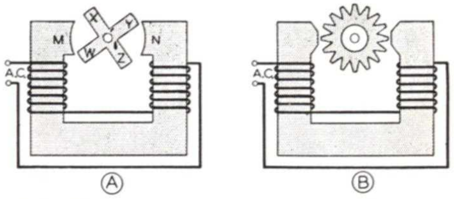


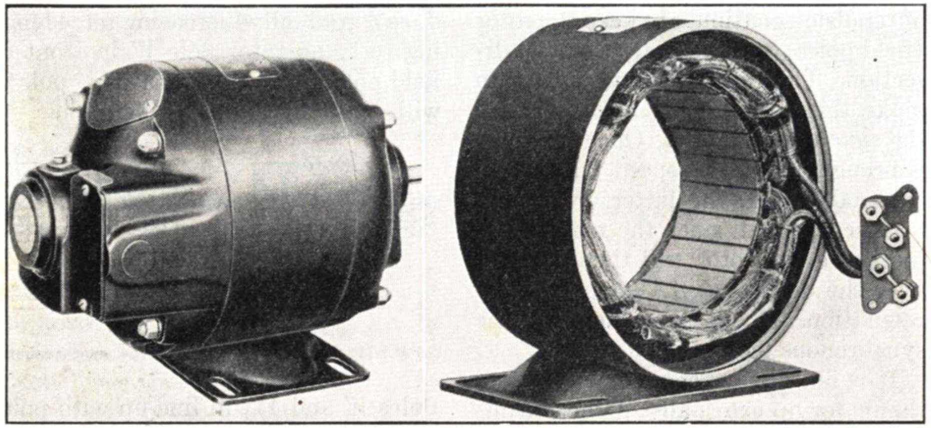
FIG. 22. Minimum-reluctance type synchronous motors.

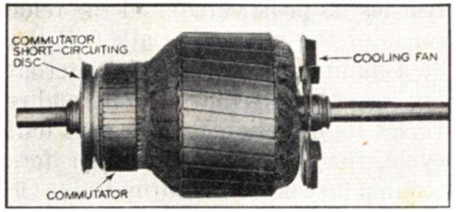
Poles *W* and *Y* will line up with poles *M* and *N* when the alternating current reaches its peak value, and the reluctance of the magnetic path will then be a minimum. Now, as the alternating current drops down to zero and reverses its direction for the next half-cycle, there will be no further force tending to rotate the armature. Obviously this type of motor is not self-starting.

If a minimum-reluctance type synchronous motor like that shown in Fig. *22A* is brought up to synchronous speed manually, the rotor will have sufficient momentum so that pole *W* will coast beyond field pole *M*. The farther beyond *M* the rotor pole gets, the less will be the attraction between the two poles, for the flux at *M* is now decreasing, and the force on *W* depends upon both the field strength and the distance between the poles. When the flux at *M* reverses and begins increasing in value again, pole *Z* will be closer than pole *W* to *M*, and we have a force which tends to keep the rotor rotating in the same direction. This same analysis applies to the toothed sixteen-pole rotor shown in Fig. *22B*. In each case, the amount of rotor rotation during each half-cycle is equivalent to the distance between two adjacent rotor poles.

The speed of minimum-reluctance type motors like those shown in Fig. *22* is calculated just as if the poles were electromagnets. If f is the frequency, P the number of poles and n the revolutions per minute, then $n = \frac{120f}{P}$. This is the same simple relation used for determining the frequency of an a.c. generator. Thus, for the four-pole rotor and a 60-cycle supply, the speed is $n = \frac{120 \times 60}{4} = 1{,}800$ r.p.m. For the sixteen-pole rotor on the same supply, the speed is $n = \frac{120 \times 60}{16} = 450$ r.p.m. Increasing the number of rotor poles employed in a synchronous motor thus *lowers the speed.*

Motors of this type have many interesting applications. As already indicated, the motors employed in clocks and constant-speed phonograph turntable drives are of this type. The national frequency standard maintained at the National Bureau of Standards employs a synchronous motor of this type in a clock operating from a submultiple of its 100-kilocycle crystals. The frequency used is 1,000 cycles per second, and the clock speed is 1,200 r.p.m. The number of teeth (poles) on the rotor is $P = \frac{120f}{n} = \frac{120 \times 1{,}000}{1{,}200} = 100$. A minimum-reluctance type a.c. motor will revolve in the direction in which it is initially started manually.





Courtesy General Electric Co

General Electric type RSA single-phase repulsion-induction a.c. motor. This unit starts as a repulsion motor, with the brushes short-circuited to give high starting torque. When operating speed is reached a centrifugal device automatically forces a short-circuiting disc against the ends of commutator bars, shorting them all together. The unit then operates as a squirrel-cage single-phase induction motor having desirable constant-speed characteristics. These motors are used extensively to drive watercooling pumps in radio stations, to drive woodworking machinery, and for other applications requiring fractional-horsepower motors with high starting torque and essentially constant speed.

The Revolving Field. Suppose that two sets of a.c. poles were used in Fig. *21*, the second set being placed between *X* and *Y* and having an independent set of windings as shown in Fig. *23*. Now if the connections to coils *L* and *M* are made through a condenser (*C*) and the connections to coils *X* and *Y* are made through a resistor (*R*), the a.c. currents in the two sets of coils can be made to have equal peak values and be approximately 90 degrees out of phase. The two a.c. fields will therefore be at right angles to each other and 90 degrees out of phase. Figure *24* shows a series of drawings each with two vectors at right angles to each other, representing the space separation of the two fields. Vector *1* represents the a.c. field produced by windings *X*-*Y* in Fig. *23*, and vector *2* the a.c. field produced by windings *L*-*M*. The 90-degree phase difference of the two fields is represented by the fact that one vector is zero when the other is a maximum, and vice versa. Note that field *1* is a maximum in one direction at *A*, is nearly zero in this same direction at *C*, and is a maximum in the opposite direction at *E*. Field *2* is nearly zero at *A*, a maximum in the same direction at *C*, and nearly zero again at *E*.

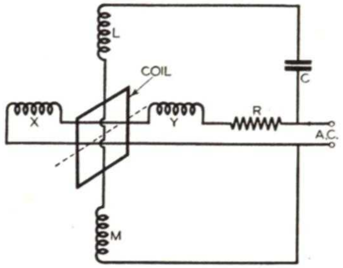
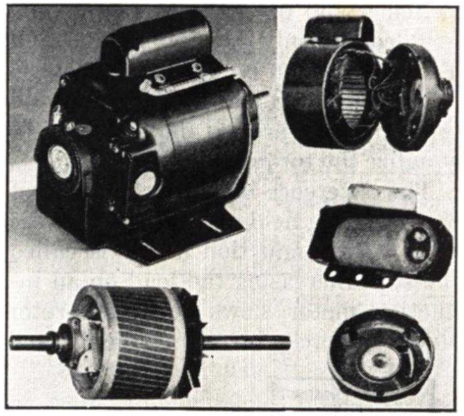


FIG. 23. Split-phase connection employed to produce a revolving magnetic field.



Courtesy General Electric Co.

These photographs show a typical split-phase a.c. induction motor and its component parts (General Electric type KH fractional-horsepower motor). These motors employ a dry electrolytic condenser (shown at the right center and usually mounted on top of the motor) to produce 90° out-of-phase fields for starting purposes. When operating speed is reached, a centrifugal device mounted on the armature releases the pressure against contacts inside one of the end castings, thereby disconnecting the starting condenser. The unit then runs as a true constant-speed single-phase induction motor. Capacitor-start induction motors provide high starting torque with relatively low starting current. They are widely used for air conditioning and cooling machinery in radio stations, for water systems, for oil burners and for a host of other low-power applications. The squirrel-cage rotor has a one-piece cast aluminum winding. Reversing the connections to the starting winding reverses the direction of rotation, for an induction motor rotates in whichever direction it is started.

If we add the two vectors in each of the cases shown in Fig. *24*, we obtain a resultant vector (*R*) of *constant amplitude* but of *continuously changing direction*. This indicates that the magnitude of the resultant field is constant but that the field revolves continuously about the armature shaft as a center.

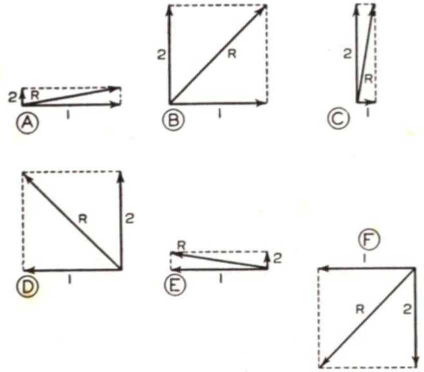


FIG. 24. The magnetic fields produced by coils at right angles to each other are shown as *1* and *2*. Since the coils are fed 90° out of phase, *1* will be a maximum when *2* is zero, and vice versa. Since each field varies cyclically we have the conditions shown in *A* to *F*. If the net field is determined by addition, taking phase into account, we get the resultant *R*, which revolves at constant strength and therefore represents a revolving field.

It is as if a field structure of the type forming poles *N* and *S* in Fig. *21* actually revolved physically.

Now refer back to Fig. *24*. The conditions depicted between *A* and *E* correspond to a half-cycle of the a.c. voltage applied to the field windings. The resultant vector (R) representing the resultant field has gone through one-half a revolution during that time. The revolving field therefore rotates at synchronous speed, making one revolution per cycle per pair of poles. Here, the number of poles making up each split phase is of importance. Thus, in the example of Fig. *23*, $n = \frac{120f}{P} = \frac{120 \times 60}{2} = 3{,}600$ r.p.m.

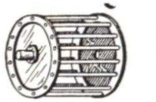


FIG. 25. Rotor of an induction motor, without the steel laminations.

We have just shown how we may obtain a magnetic field revolving in space even though the field coils producing it are stationary. This is called a *revolving field*. The winding arrangement of the field coils is called a *split-phase connection*. Let us see how it can be used.

The Split-Phase Induction Motor. If a short-circuited coil is in the field structure of Fig. *23*, the revolving field, passing this coil, changes the flux threading it and induces a voltage. The voltage sets up a current in the short-circuited coil which, by Lenz's law, tends to oppose the field producing it. The result is a force on the coil which rotates it in the direction of the revolving field. If the coil should catch up to the field (i.e., rotate at synchronous speed), there would no longer be any change of flux threading it. The force on it would reduce to zero and it would tend to slow down. It slows down until its torque is sufficient for whatever mechanical load is applied to its shaft. This is the principle of the split-phase circuit so widely used for starting induction motors.

Once a split-phase induction motor is brought nearly up to synchronous speed, it is no longer necessary to have two fields 90° out of phase with each other in the stationary armature. The reason is simply that the rotor itself is now producing its own magnetic field (due to the change in flux linkages through the shorted rotor coils as they rotate in the oscillating field produced by alternating current flowing through one pair of stationary armature poles), and this rotor-produced magnetic field reacts with the stationary oscillating field to produce *a revolving magnetic field* which is essentially constant in strength. This is the true induction motor action.

A rotor-produced revolving field exists in all induction motors once they are brought up to synchronous speed by some means, and in most cases is the only revolving field used to maintain rotation at full load. The starting circuit is disconnected by a centrifugally-operated switch as soon as a certain speed is reached; in Fig. *23* this switch would open the condenser circuit, leaving only the main poles X and Y to produce an oscillating stationary field. These two main windings would be distributed around the armature to equalize the torque.

The difference between the speed of the revolving field and the speed of the rotor in an induction motor is called the slip. Increasing the load on an induction motor slows down the rotor slightly, thereby increasing the slip and producing the increased rotor currents necessary to handle the extra load. The slip cannot be more than about 5% of the synchronous speed, if rotation is to be maintained; when the increase in load is so great that slip exceeds this value, the motor stops.

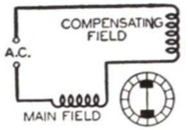


FIG. 26. Circuit of an a.c repulsion-induction motor.

In commercial induction motors, a large number of short-circuited loops are employed on the armature, to secure more uniform torque. A typical rotor is shown in Fig. *25*. Speed may be controlled by inserting resistors in series with the rotor loops; this is possible when the rotor is made up of coil elements which are connected to slip rings on the rotor shaft. The greater the resistance, the lower the speed.

A.C. Repulsion-Induction Motor. A d.c. motor may act as a combination repulsion-induction a.c. motor. It starts as a repulsion motor with the brushes short-circuited; as it approaches synchronous speed, the short between the brushes is automatically opened, giving an induction motor. Instead of shifting the brushes to one side as shown in Fig. *20*, the brushes are usually left at neutral and a compensating field is used to provide a 90-degree out-of-phase field, as indicated in Fig. *26*. This provides the off-neutral field required to give starting torque. When the armature gets up to nearly full speed (synchronous minus slip), the brushes are raised by a centrifugal device, and at the same time all the segments on the commutator are shorted. The action from now on is that of an induction motor.

Self-Starting Synchronous Motor. A single-phase synchronous motor may be made self-starting. A split-phase a.c. field connection is employed for obtaining a revolving field, and short-circuited coils are embedded in the d.c. field structure (at poles N and S in Fig. *21*) to provide an auxiliary armature. The machine starts as a split-phase induction motor. As it comes up to nearly synchronous speed, the d.c. magnetic system locks into step with the revolving field and rotates at synchronous speed.

TEST QUESTIONS

Be sure to number your Answer Sheet 27RC.

Place your Student Number on every Answer Sheet.

Most students want to know their grades as soon as possible, so they mail their answers immediately. Others, send in two sets at a time. Either practice is acceptable, but don't hold your answers too long; you may lose them or run out of lessons before new ones can reach you.

1. What four factors control the voltage induced in a system of conductors moving in a magnetic field?
2. What is the purpose of the commutator in a d.c. generator?
3. In what direction from the dead-center position should the brushes of a d.c. generator be moved in order to minimize sparking?
4. How can a small a.c. generator be made self-excited?
5. What is meant by the term "voltage regulation" in connection with a generator?
6. Why are series and shunt field coils sometimes used together in a d.c. generator?
7. Why does the armature current in a d.c. motor decrease as the motor comes up to operating speed?
8. What will happen if the field circuit of a shunt-excited d.c. motor is opened while the motor is driving a very small load?
9. Will the direction of rotation of a series d.c. motor be reversed if the polarity of the applied voltage is reversed?
10. What happens to the speed of a synchronous motor when the number of rotor poles is increased?

DELIVER THE GOODS

"There are 57 rules for success. The first is to deliver the goods. Never mind the rest."

Like many striking assertions, the quotation above is not altogether true, because there are other rules which cannot be ignored. But there is a lot of truth in this statement.

If you want to be a success in life, deliver the goods. Employers want men who *earn* their salary each and every day—men who have the training required for their particular jobs and actually do apply this training to their work.

You can always excuse yourself if you fail—but nobody else will ever excuse you. Customers may be polite to you and may feel sorry for you, but they will go elsewhere the next time they need radio service work. Employers are equally indifferent to excuses, for they must have good men if they themselves are to deliver the goods.

Make it your business to be where you are needed, when you are needed, with the service or help that is needed. Have all the knowledge which may be required. Be the man who delivers the goods and gets the money.

J. E. SMITH