10

Principles of Direct-Current Machines

10.1 INTRODUCTION

The DC motor is the most versatile of all rotating electrical machines. Its speed may be easily adjusted in very fine increments ranging from standstill to rated speed and above, and if not properly controlled, may reach speeds high enough to cause destruction by centrifugal force. Direct-current motors can develop rated torque at all speeds from standstill (locked-rotor) to rated speed, and the torque that it can develop at standstill is many times greater than the torque developed by an AC motor of equal power and speed ratings.

Direct-current motors are used in a wide variety of industrial drives, such as robots, machine tools, petrochemical, pulp, paper and steel mills, oil drilling rigs, and mining. They are also used extensively in automotive systems and railroads.

Direct-current generators, however, once the mainstay of electric power for large and small industrial plants, are being increasingly replaced by solid-state devices that convert available AC to direct current for DC drive systems and other DC applications.

10.2 FLUX DISTRIBUTION AND GENERATED VOLTAGE IN AN ELEMENTARY DC MACHINE

The flux distribution in the air gap of an elementary two-pole DC machine is shown in Figure 10.1. Except for the interpolar region, the pole face of a DC machine is shaped to provide a uniform flux distribution per space degree in the air-gap region between the pole face and the armature. Although there is some fringing of flux in the interpolar region, there is no flux entering or leaving the armature in the magnetic-neutral plane (plane of zero flux).

Figure 10.2(a) shows several positions of an armature coil as it revolves counterclockwise (CCW) within the magnetic field, and Figure 10.2(b) shows the corresponding variation of flux through the window of the armature coil plotted against electrical degrees.

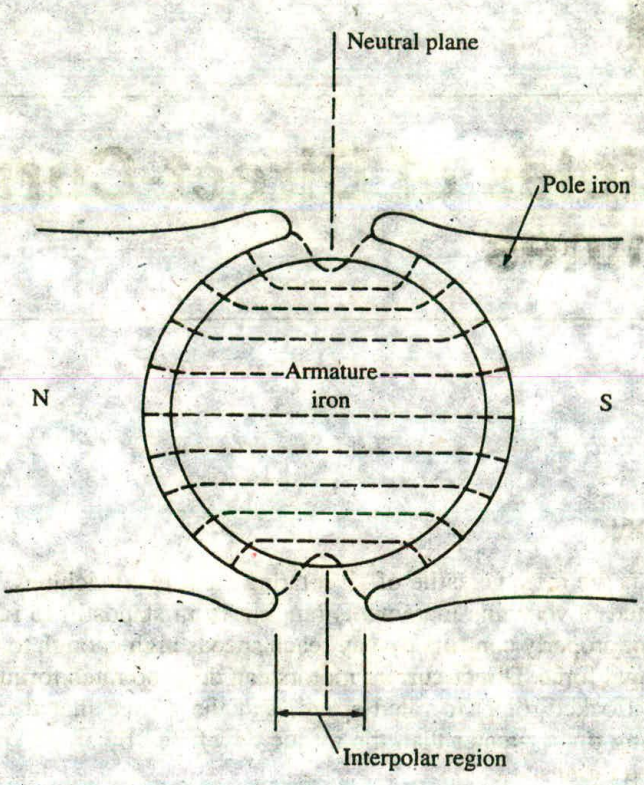


FIGURE 10.1
Flux distribution in the air gap of an elementary DC machine.

At zero degrees all of the flux that crosses the air gap passes through the armature coil. As the coil rotates from the zero-degree position, the amount of flux passing through the window decreases linearly with angular position until at 90° the flux through the window is zero. When past the 90° position, the flux passes through the opposite face of the coil. The flux increases linearly to its maximum value in the opposite direction at 180°, then decreases, reaching zero at 270°, and so forth. Except for small changes in flux in the interpolar region, the graph of flux through the coil window as a function of rotation angle is triangular in shape.

In accordance with Faraday's law, the magnitude of the voltage generated in the armature coil is equal to the number of turns of wire in the coil times the rate of change of flux through the coil window. Furthermore, in accordance with Lenz's law, the voltage will be generated in a direction to oppose the rotation that caused it. The combined *Faraday–Lenz* relationship is expressed as

$$e = -N_a \frac{d\phi}{dt} \tag{10–1}$$

The minus sign in Eq. (10–1) is the application of Lenz's law to the Faraday equation.

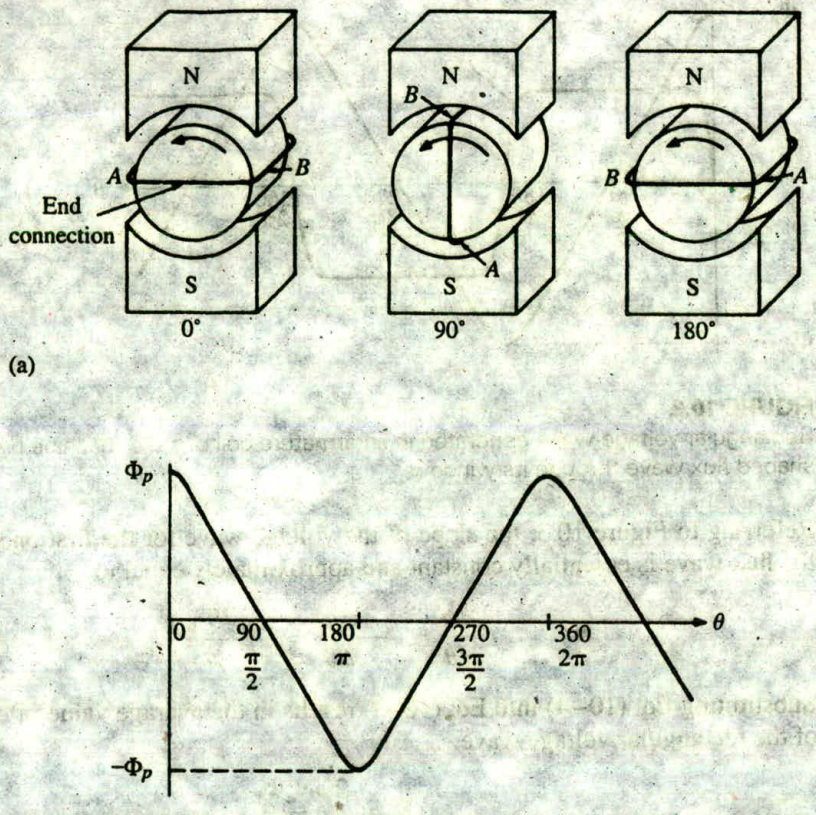


FIGURE 10.2
(a) Representative positions of an armature coil; (b) plot of flux through the window of an armature coil vs. angular position of coil.

Applying the Faraday–Lenz relationship to the triangular-shaped flux wave in Figure 10.2(b) results in the rectangular-shaped voltage wave shown in Figure 10.3. The angular velocity of the coil as it rotates at constant speed is

$$\omega = \frac{d\theta}{dt} \quad \Rightarrow \quad dt = \frac{d\theta}{\omega} \tag{10–2}$$

Substituting Eq. (10–2) into Eq. (10–1),

$$e = -N_a \omega \frac{d\phi}{d\theta} \tag{10–3}$$

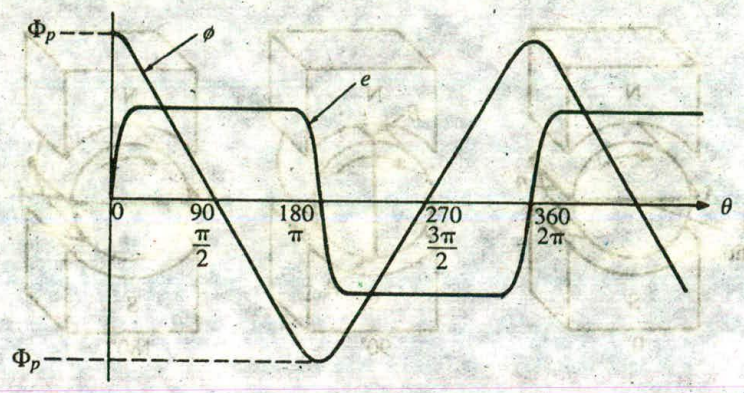


FIGURE 10.3
Rectangular voltage wave generated in an armature coil of a DC machine by a triangular-shaped flux wave through its window.

Referring to Figure 10.3, the slope of the voltage wave for the first one-half cycle of the flux wave is essentially constant and approximately equal to

$$\frac{d\phi}{d\theta} = -\frac{\Delta\phi}{\Delta\theta} = -\frac{2\Phi_p}{\pi} \qquad \textbf{(10–4)}$$

Substituting Eq. (10–4) into Eq. (10–3) results in the average value of one-half cycle of the rectangular voltage wave:

$$E_a = \frac{2\omega N_a \Phi_p}{\pi} \qquad \textbf{(10–5)}$$

Rectifying the rectangular-shaped voltage wave by solid-state or mechanical methods results in the wave shown in Figure 10.4, and Eq. (10–5) applies to the entire wave. Equation (10–5) can be expressed in terms of r/min by making the following substitutions:

$$\omega = 2\pi f \qquad \textbf{(10–6)}$$

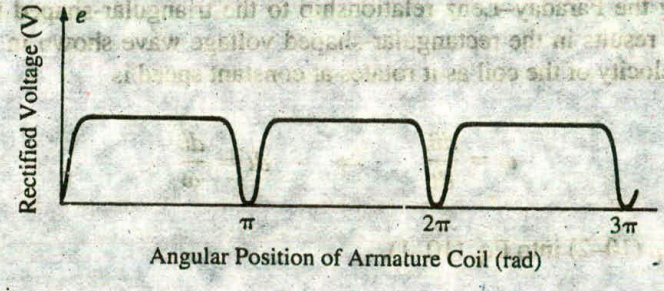


FIGURE 10.4
Rectified voltage wave.

$$f = \frac{Pn}{120} \tag{10–7}$$

Thus,

$$E_a = \frac{nPN_a\Phi_p}{30} \tag{10–8}$$

where: E_a = voltage induced in armature (avg) (V)
f = frequency (Hz)
n = rotational speed (r/min)
P = number of field poles
Φ_p = pole flux (Wb)
N_a = number of turns of conductor in armature

Each turn of wire in an armature coil has two conductors (coil sides). No voltage is generated in the end connections; the end connections (also called end turns) do not "cut" flux (see Figure 10.2). Thus, in terms of armature conductors,

$$N_a = \frac{z_a}{2} \tag{10–9}$$

where z_a = the total number of armature conductors.

A practical machine has many coils of wire that are distributed around the armature in series–parallel arrangements, with a minimum of two parallel paths. An expression for the average value of induced emf, in terms of total armature conductors, is obtained by substituting Eq. (10–9) into Eq. (10–8). Making the substitution,

$$E_a = \frac{nPz_a\Phi_p}{60a} \tag{10–10}$$

where: a = number of parallel paths
z_a = total number of armature conductors

The number of parallel paths and the number of series-connected conductors required for a given kilowatt rating are determined by the system voltage; low-voltage, high-current machines have more parallel paths, each with fewer series-connected conductors than high-voltage, low-current machines.

Substituting k_G for the constants in Eq. (10–10),

$$k_G = \frac{z_aP}{60a} \tag{10–11}$$

$$E_a = n\Phi_pk_G \tag{10–12}$$

EXAMPLE 10.1 A six-pole, 50-kW, DC machine operating at 1180 r/min has a generated emf of 136.8 V. If the speed is reduced to 75 percent of its original value, and the pole flux is doubled, determine (a) induced emf; (b) frequency of the rectangular voltage wave in the armature winding.

Solution

(a) From Eq. (10–12),

$$\frac{E_1}{E_2} = \frac{[n\Phi_p]_1}{[n\Phi_p]_2} \quad \Rightarrow \quad E_2 = E_1 \times \frac{[n\Phi_p]_2}{[n\Phi_p]_1}$$

$$E_2 = 136.8 \times \frac{0.75n \times 2\Phi_p}{n \times \Phi_p} = \underline{205.2 \text{ V}}$$

(b)
$$f = \frac{Pn}{120} = \frac{6 \times 1180 \times 0.75}{120} = \underline{44.25 \text{ Hz}}$$

10.3 COMMUTATION

The rectangular-shaped voltage wave generated within a DC armature coil is changed to a unidirectional voltage in the load circuit by means of a mechanical rectifier, called a *commutator,* mounted on the armature shaft. This is illustrated in Figure 10.5 for an elementary two-pole DC machine with one armature coil and a two-bar commutator. Connections to the external terminals are made via small stationary blocks of graphite, called *brushes,* that are pressed against the commutator by springs.

As shown in Figure 10.5, the generated voltage within the armature coil changes direction every 180 electrical degrees of rotation, but the voltage in the external circuit remains in the same direction. The rotating commutator and stationary brushes constitute a rotary switch that provides a switching action, called *commutation,* that switches the internal alternating voltage and current of an AC generator to direct voltage and direct current in the external circuit.

When the coil is rotating through the neutral plane, as shown in Figures 10.5(a) and (c), it is shorted by the brushes. Since the coil sides are not cutting flux, however, no armature voltage is generated, and no short-circuit current occurs.

A practical machine has many coils distributed around the armature, and the coils pass through the neutral plane one at a time. As one coil moves into the neutral plane another moves out, producing an essentially constant voltage.

10.4 CONSTRUCTION

A cutaway view of a DC machine is shown in Figure 10.6. The shunt field coils and series field coils[1] are wound around the same pole iron and provide the specific machine characteristics. Some DC machines omit the shunt field coils and use permanent magnets for the pole iron; in such cases, the series field would be wound around the magnets.

[1]Series fields are used in compound and series machines to shape motor and generator characteristics. See Chapters 11 and 12, respectively, for further details.

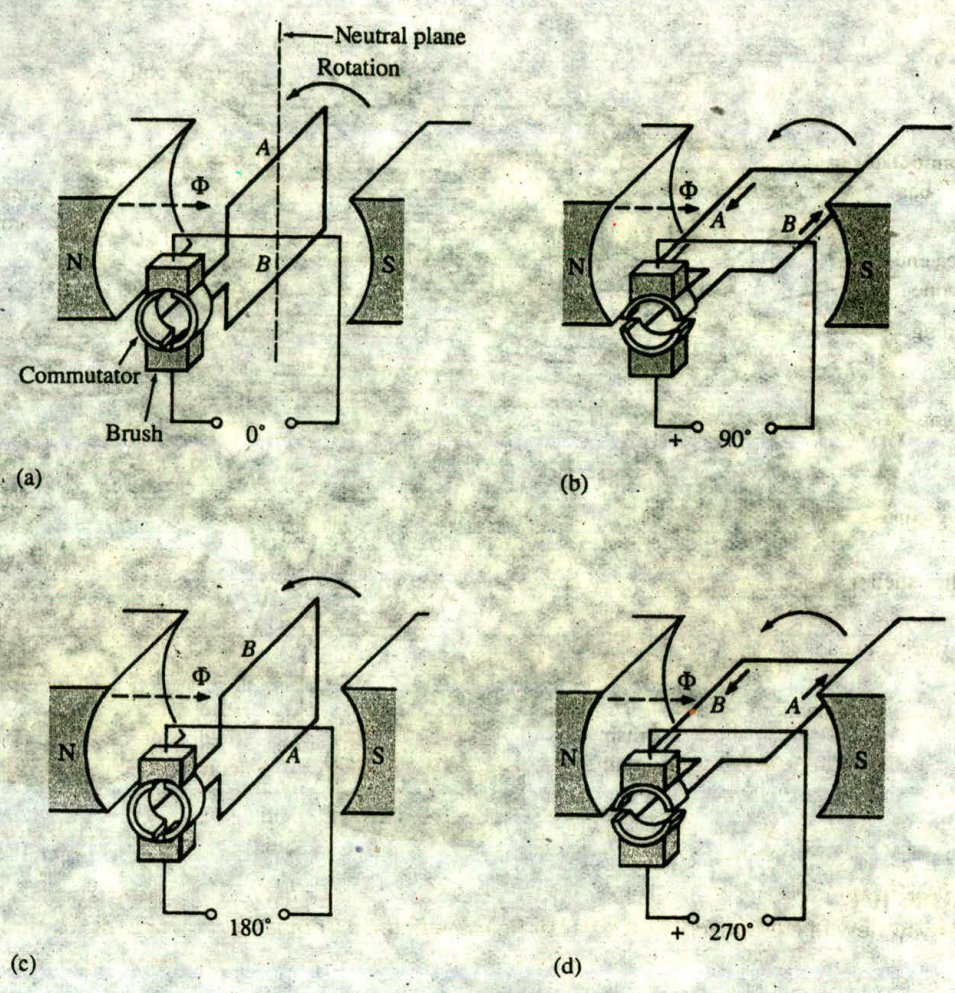


FIGURE 10.5
Sketches showing the commutation process illustrated with a one-coil armature.

Small poles, called *interpoles* or *commutating poles,* are located between the main field poles. The interpoles are used to minimize sparking between the brush and the commutator, which would otherwise occur when the machine is loaded. The interpole iron and main-pole iron are bolted to a yoke or frame of cast steel. Graphite or metal–graphite brushes provide the connection between the rotating commutator and the external load; they are designed to slide freely in metallic brush-boxes, and are connected to the box by a short flexible copper conductor called a *pigtail* or *shunt.*

The commutator is composed of alternate sections of copper bars and mica separators, clamped together with mica-insulated vee-rings. The number of commutator bars is determined by the number of coils in the armature, the number of poles, and the type of winding.

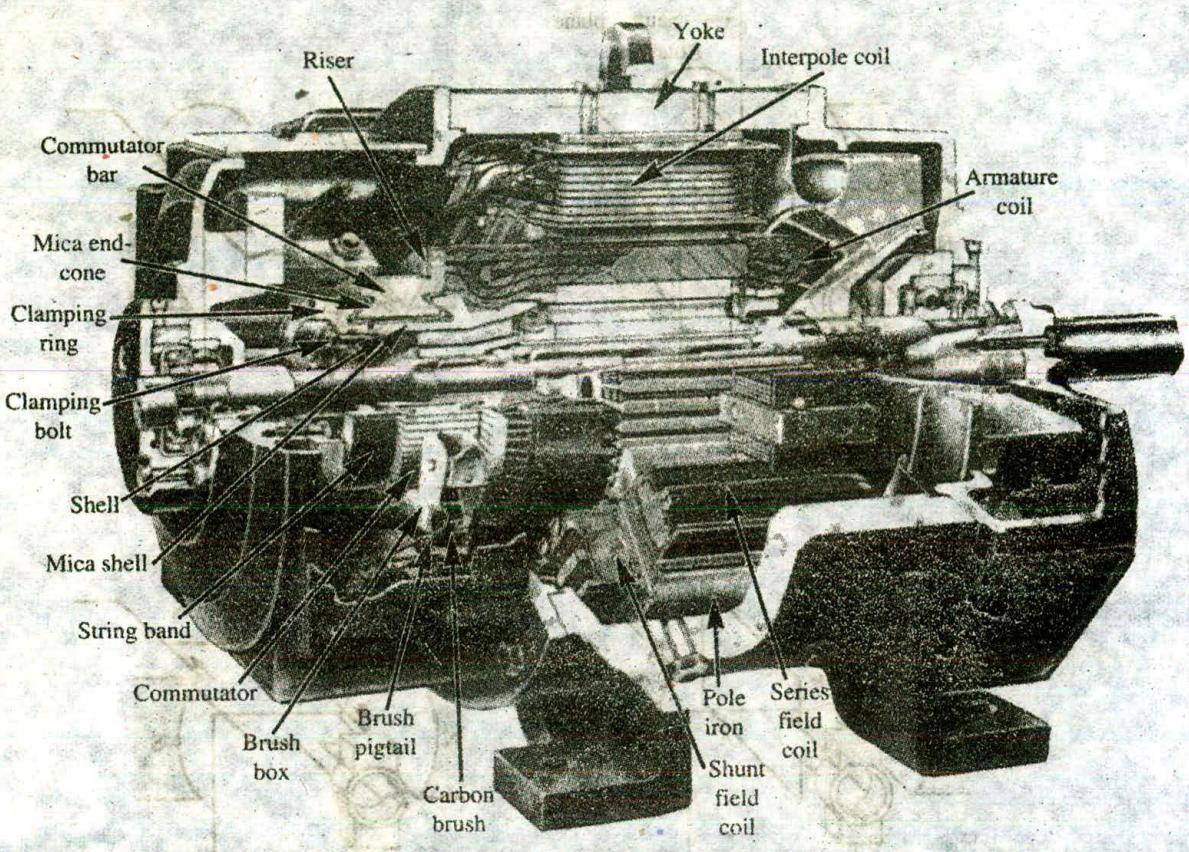


FIGURE 10.6
Cutaway view of a DC machine. (Courtesy Reliance Electric Company)

10.5 LAYOUT OF A SIMPLE ARMATURE WINDING

Figure 10.7 illustrates the layout of a simple armature winding (called a *lap winding*) for an eight-slot, eight-coil armature designed for operation with a two-pole field. Figure 10.7(a) shows the layout of the armature winding and its connections to the commutator, Figure 10.7(b) shows the physical layout of the top and bottom conductors in the armature slots, and Figure 10.7(c) is an elementary diagram that shows how the brushes form two parallel paths in the armature. The letters T and B refer to the top and bottom conductors in a single slot. For example, as seen in Figure 10.7(a), one side of coil 1 is in the top of slot 1, and the other side is in the bottom of slot 5.[2]

[2]For more information on armature windings, see the General References section at the end of this chapter.

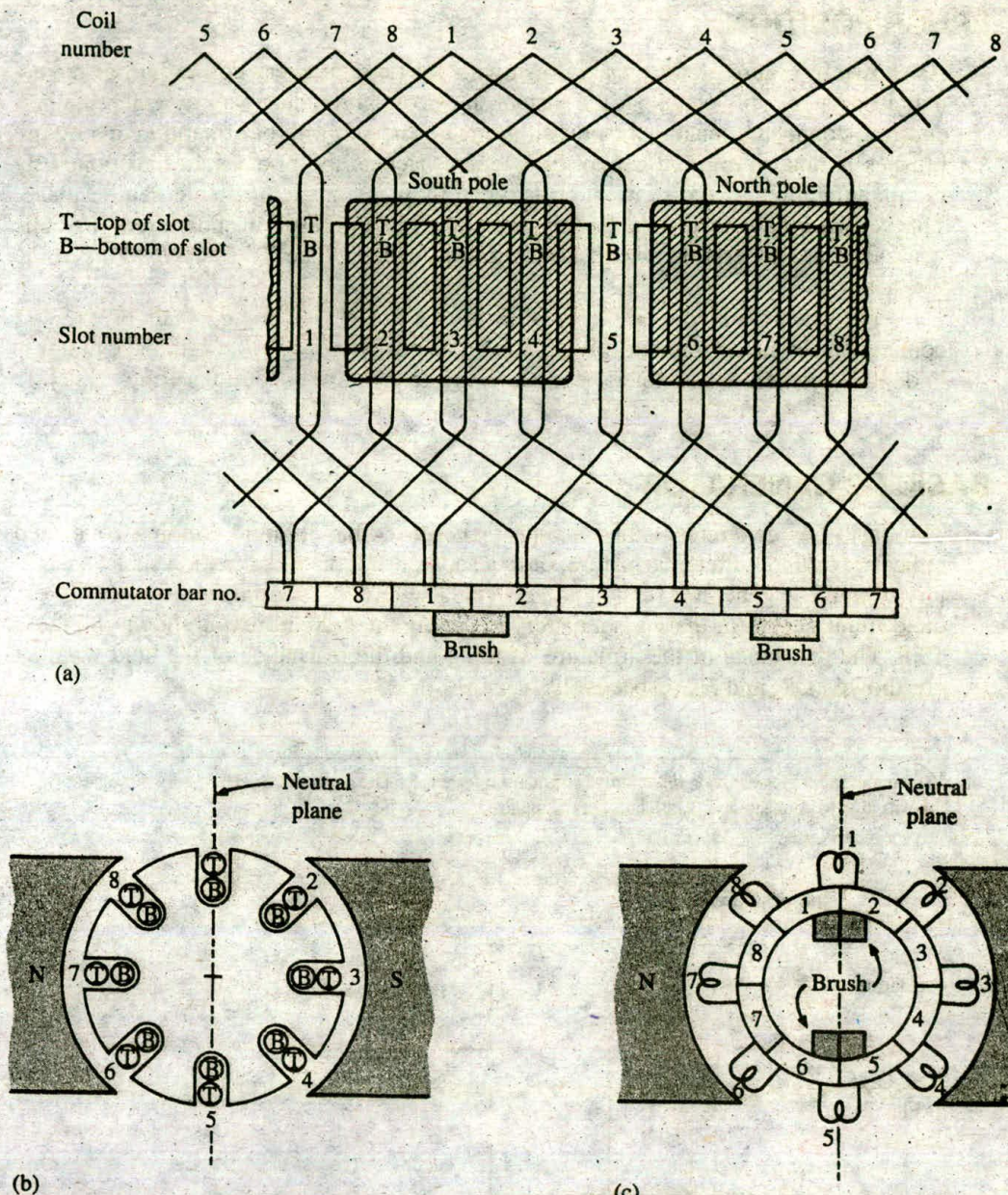


FIGURE 10.7
Layout of a simple armature winding: (a) coil distribution and commutator connections; (b) end view of an armature showing top and bottom conductors; (c) simplified connection diagram showing neutral plane and brush position.

10.6 BRUSH POSITION

As shown in Figure 10.7(c), each brush will short circuit every coil in turn as the armature rotates. This occurs at the instant the two commutator bars to which the coil ends are connected make contact with a brush. The shorting of armature coils by the brushes is undesirable but cannot be avoided. Hence, the brushes are positioned by the manufacturer to short circuit coils when they are in the magnetic neutral plane. This is called the *neutral setting*. Any other position will result in short circuiting coils while they are generating an emf, causing overheating of the coils and sparking at the brushes.

The physical layout of the brushes in any given machine depends on the coil connections to the commutator. When the brush position of a DC generator or motor is in doubt, electrical tests should be made to locate the correct neutral setting [1],[2].

10.7 BASIC DC GENERATOR

The basic DC generator, called a *shunt generator*,[3] has its field winding connected either in parallel with the armature, or to a separate source of excitation such as a battery or another generator (called an *exciter*). The circuit diagram for a separately excited shunt generator that uses a battery to supply the field current is shown in Figure 10.8. The resistance of the armature winding and the resistance of the field winding are shown as R_a and R_f, respectively.

[3] The name *shunt generator* or *shunt motor* originally referred to a DC generator or DC motor whose field winding was always connected in parallel with the armature.

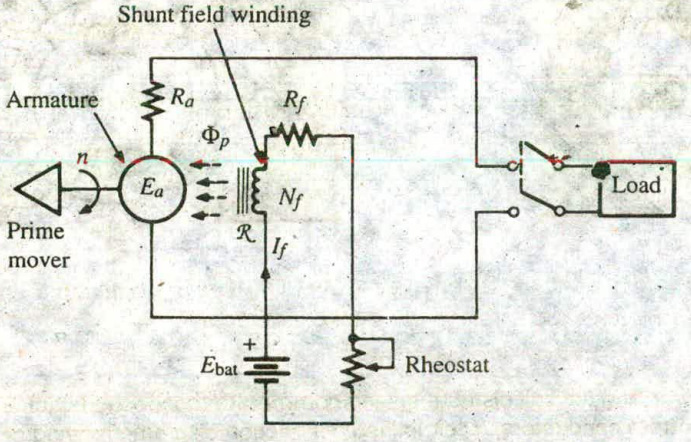


FIGURE 10.8
Equivalent-circuit diagram for a separately excited shunt generator.

Neglecting any residual magnetism, which is designed to be negligible for a separately excited machine, the pole flux can be determined from

$$\Phi_p = \frac{N_f I_f}{\mathcal{R}} \tag{10–13}$$

where: I_f = field current (A)
N_f = number of turns of wire in a field coil
$\mathcal{R}$ = reluctance of magnetic circuit (A-t/Wb)
Φ_p = pole flux (Wb)

Substituting Eq. (10–13) into Eq. (10–12),

$$E_a = \frac{aN_f I_f k_G}{\mathcal{R}} \tag{10–14}$$

Note that the reluctance $\mathcal{R}$ of the ferromagnetic material is not constant. Hence, Eq. (10–14) is nonlinear.

The current in the field windings as determined from Ohm's law is

$$I_f = \frac{E_{\text{bat}}}{R_f + R_{\text{rheo}}} \tag{10–15}$$

where: I_f = field current (A)
E_{bat} = battery voltage (V)
R_f = resistance of field winding, including all poles (Ω)
R_{rheo} = resistance of rheostat, at setting (Ω)

Reducing the rheostat resistance increases the field current, which in turn increases the pole flux, causing an increase in the armature voltage.

The relationship between field current and induced armature voltage is shown graphically in Figure 10.9 for a representative DC machine. The curve, called the *magnetization curve* or *open-circuit characteristic,* is a plot of E_a vs. I_f as expressed in Eq. (10–14), assuming constant speed and no load connected to the armature terminals.

EXAMPLE 10.2 Assume that the resistance of the armature winding and the resistance of the field winding of the generator shown in Figure 10.8 are 0.014 Ω and 10.4 Ω, respectively, and that the magnetization curve is the one shown in Figure 10.9. Determine the rheostat setting required to obtain an induced emf of 290 V. The battery voltage is 240 V.

Solution

The required field current, as obtained from the magnetization curve in Figure 10.9, is ≈8.9 A. Applying Ohm's law to the shunt field circuit,

$$I_f = \frac{E_{\text{bat}}}{R_f + R_{\text{rheo}}} \quad \Rightarrow \quad R_{\text{rheo}} = \frac{E_{\text{bat}}}{I_f} - R_f$$

$$R_{\text{rheo}} = \frac{240}{8.9} - 10.4 = \underline{16.57}$$

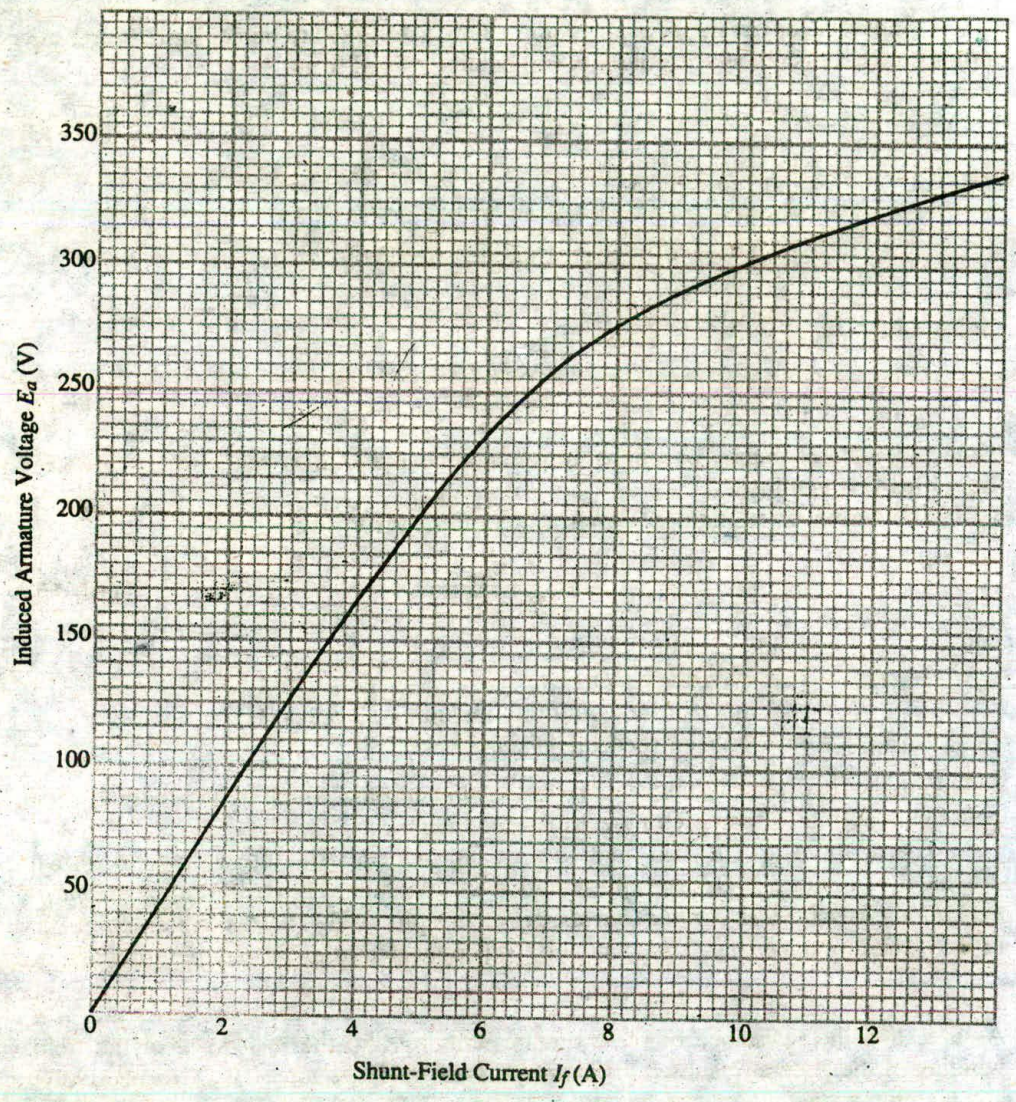


FIGURE 10.9
Magnetization curve for a representative separately excited shunt generator.

10.8 VOLTAGE REGULATION

The voltage regulation of a DC generator is the percent change in terminal voltage from no load to rated load, with respect to rated voltage:

$$\text{VR} = \frac{V_{\text{nl}} - V_{\text{rated}}}{V_{\text{rated}}} \times 100 \qquad \textbf{(10–16)}$$

where: VR = voltage regulation (percent)
V_{nl} = no-load (open-circuit) voltage (V)
V_{rated} = voltage indicated on nameplate of machine (V)

The no-load voltage may be obtained by operating the machine at its nameplate conditions, then removing the load and observing the no-load voltage. Although this is an exact method, it is not practical for very large machines.

An analytical method that provides a good approximation of the no-load voltage may be determined from the machine parameters and the associated magnetization curve (see Chapter 12).

EXAMPLE 10.3 A 100-kW, 1800 r/min generator operating at rated load has a terminal voltage of 240 V. If the voltage regulation is 2.3 percent, determine the no-load voltage.

Solution

$$\text{VR} = \frac{V_{nl} - V_{rated}}{V_{rated}} \quad \Rightarrow \quad V_{nl} = V_{rated} \times (1 + \text{VR})$$

$$V_{nl} = 240 \times (1 + 0.023) = \underline{245.5 \text{ V}}$$

10.9 GENERATOR-TO-MOTOR TRANSITION AND VICE VERSA

Generator-to-motor transition and vice versa are illustrated in Figure 10.10 using an elementary DC machine. For simplicity, only one armature coil is shown, and the magnetic field is supplied by permanent magnets. The armature is connected to a battery through the DC bus. The prime mover, which may be a steam turbine, diesel engine, etc., is mechanically coupled to the armature through a clutch. The clutch shown in Figure 10.10 is used for illustrative purposes. In actual practice the generator is directly coupled to the prime mover.

Generator Action

In Figure 10.10(a), the clutch is closed and the prime mover is shown driving the armature at a speed that causes its emf to be greater than the battery voltage. Since $E_a > E_{bat}$, the machine behaves as a generator, feeding current to the bus, charging the battery. The direction of current in the armature conductors, for the given magnetic polarity and direction of armature rotation, is determined by Lenz's law and the flux bunching rule. The equivalent circuit for generator action is shown in Figure 10.10(b). Resistor R represents the resistance of the armature windings, battery, and connecting cables.

Motor Action

Disengaging the prime mover by opening the clutch causes the armature speed and hence the generated emf to decrease. When the speed drops to a value that causes

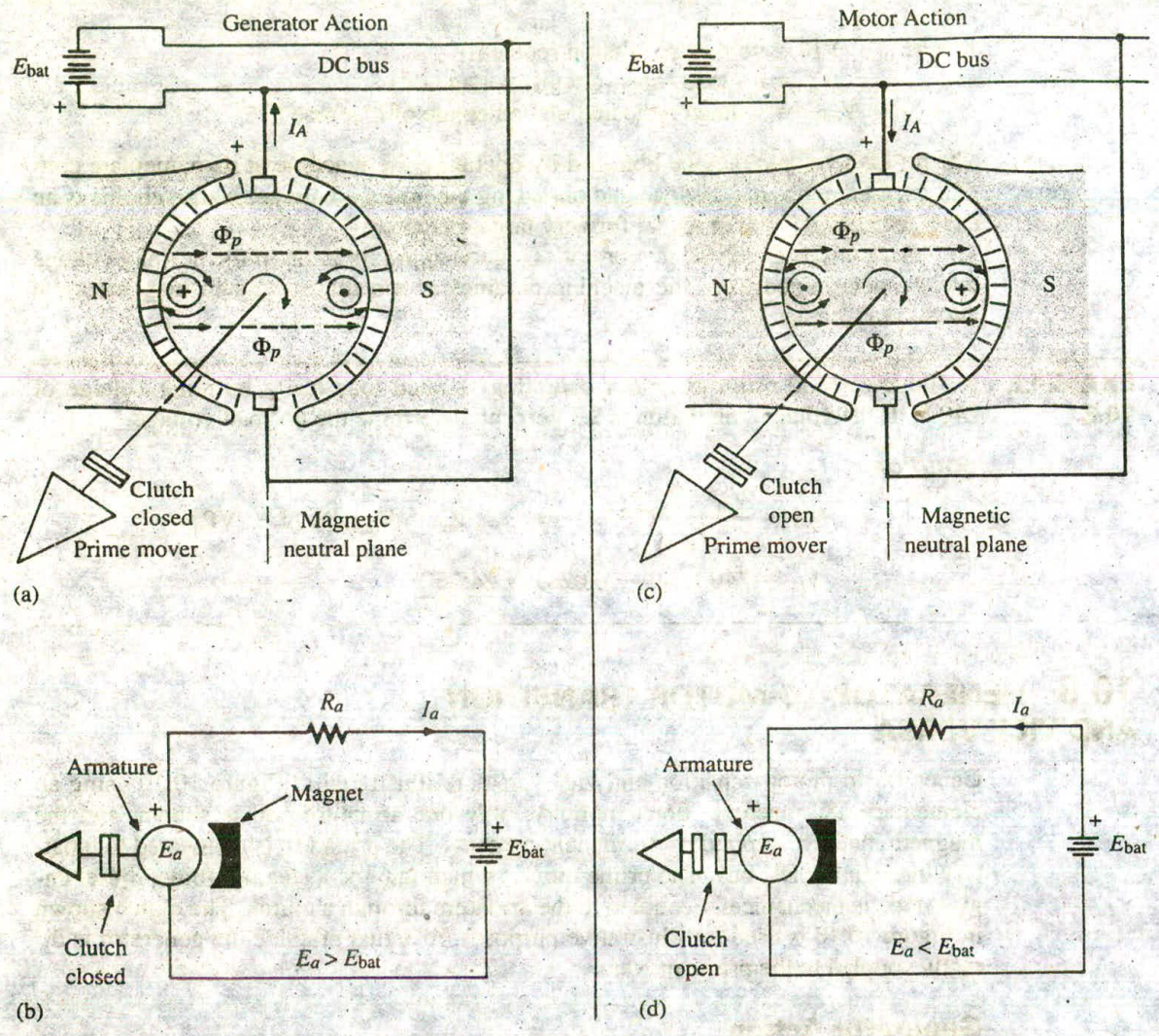


FIGURE 10.10
Generator-to-motor transition: (a) and (b) generator action; (c) and (d) motor action.

$E_a < E_{bat}$, the battery will act as the source, reversing the current in the armature and driving the machine as a motor. This is shown in Figure 10.10(c). Note that the rotation of the armature when motoring is in the same direction as it was when driven by the prime mover. The direction of rotation may be verified by Lenz's law and the flux bunching rule. Furthermore, as indicated in Figures 10.10(b) and (d), *the direction of the induced emf* (E_a) *is the same whether the machine is operating as a motor or as a generator;* this must be so, because in both cases the magnet polarity and the direction of rotation are the same.

All rotating machines (generators and motors) generate voltage *and* develop torque. When acting as a generator, as shown in Figures 10.10(a) and (b), the machine generates voltage, and if supplying current, develops a countertorque in opposition to the driving torque. When acting as a motor, as shown in Figures 10.10(c) and (d), the machine develops a driving torque, and if the shaft is free to turn, generates a counter-voltage (called a counter-emf or cemf) in opposition to the driving voltage. Furthermore, the machine will rotate in the same direction whether motoring or acting as a generator; the only outward indication of a change in the operating condition is the reversal of armature current, as would be indicated on an ammeter.

10.10 REVERSING THE DIRECTION OF ROTATION OF A DC MOTOR

The direction of rotation of a direct-current motor may be reversed by reversing either the current in the armature or the polarity of the field, but not both. Figures 10.11(a) and (b) illustrate how reversing the armature current reverses the direction of rotation. Figures 10.11(c) and (d) illustrate how reversing the polarity of the field reverses the direction of rotation. The direction of rotation in each case may be determined by the flux bunching rule, as shown on the inset in each figure.

10.11 DEVELOPED TORQUE

The relationship between developed torque, conductor current, and flux density, derived in Section 1.10 of Chapter 1 for an elementary motor, applies to all motors. Thus, by extension,

$$T_D = B_p I_a k_M \qquad \textbf{(10–17)}$$

where: B_p = flux density in air gap produced by shunt field poles (T)
I_a = armature current (A)
k_M = constant

Constant k_M depends on the design of the motor and includes the number of turns, effective length of armature conductors, number of poles, type of internal circuitry, and units used.

As indicated in Eq. (10–17) the torque developed by a DC motor is proportional to the flux density in the air gap and the current in the armature.[4]

10.12 BASIC DC MOTOR

The equivalent-circuit diagram for the basic DC motor, called a shunt motor, is shown in Figure 10.12. The shunt field winding is connected across the incoming lines, and it provides the flux that interacts with the armature current to produce the torque that results in motor action.

[4] The required flux density in the air gap of a DC machine depends on its power and speed ratings, and varies from a low of approximately 0.5 T to slightly over 1.0 T for large machines [3].

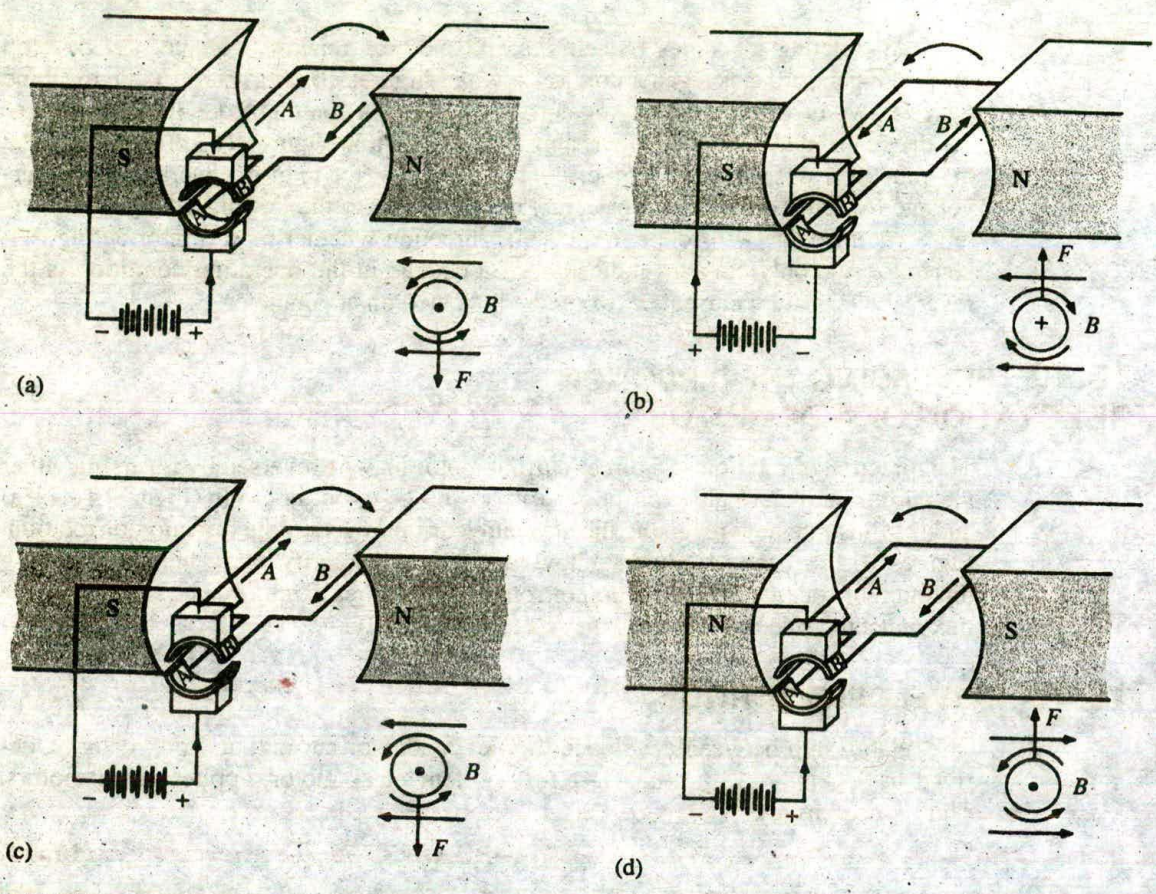


FIGURE 10.11
Reversing a direct-current motor by (a) and (b) reversing the armature current; (c) and (d) reversing the polarity of the field.

The shunt field does no useful work. It merely provides the necessary medium for the armature conductors to push against when developing rotary motion. It is similar to the roadbed against which the wheels of an automobile push; the roadbed does no work, but without it the car could not move. All of the energy supplied to the field is expended as I^2R losses in the field windings. This may be easily shown by connecting a wattmeter to measure the power drawn by the shunt field. Observation of the wattmeter will indicate no change in the power input to the field as the machine is loaded. A wattmeter placed in the armature circuit, however, will indicate proportional increases in power with increased shaft load. Assuming the developed torque is sufficient to cause rotation, a cemf will be generated in the armature that is proportional to the armature speed and the air-gap flux. That is,

$$E_a = n\Phi_p k_{G_a} \qquad \textbf{(10–18)}$$

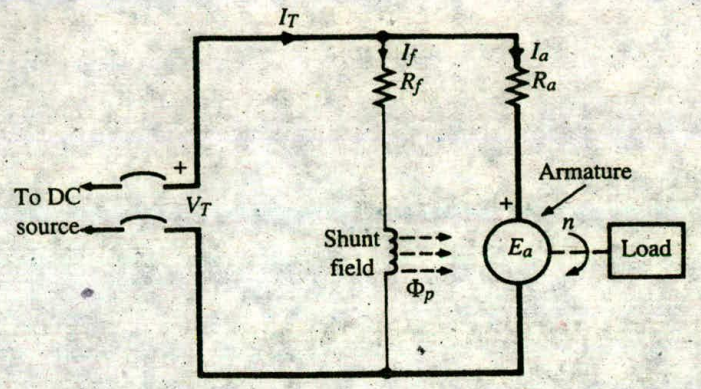


FIGURE 10.12
Equivalent-circuit diagram for a basic DC motor.

where Φ_p = flux in air gap produced by shunt field poles (Wb). Solving Eq. (10–18) for armature speed,

$$n = \left.\frac{E_a}{\Phi_p k_G}\right|_{\Phi_p \neq 0} \tag{10–19}$$

Within the constraints indicated in Eq. (10–19), the speed of a DC motor is inversely proportional to the pole flux.

Note: If $\Phi_p = 0$, then the motor torque as indicated in Eq. (10–17) will be zero, and the armature will not turn.

Applying Kirchhoff's voltage law to the armature circuit in Figure 10.12 and solving for the current,

$$V_T = I_a R_a + E_a$$

$$I_a = \frac{V_T - E_a}{R_a}$$

EXAMPLE 10.4 A 240-V, 20-hp, 850 r/min shunt motor draws 72 A when operating at rated conditions. The respective resistances of the armature and shunt field are 0.242 Ω and 95.2 Ω. Determine the percent reduction in field flux required to obtain a speed of 1650 r/min, while drawing an armature current of 50.4 A.

Solution

$$I_{f1} = \frac{240}{95.2} = 2.52 \text{ A}$$

$$I_{a1} = I_T - I_{f1} = 72 - 2.52 = 69.48 \text{ A}$$

$$E_{a1} = V_T - I_{a1} R_a = 240 - 69.48 \times 0.242 = 223.19 \text{ V}$$

$$E_{a2} = V_T - I_{a2} R_a = 240 - 50.4 \times 0.242 = 227.80 \text{ V}$$

$$n_2 = n_1 \cdot \frac{[E_a/\Phi_p]_2}{[E_a/\Phi_p]_1} \quad \Rightarrow \quad \Phi_{p2} = \frac{n_1}{n_2} \times \frac{E_{a2}}{E_{a1}} \times \Phi_{p1}$$

$$\Phi_{p2} = \frac{850}{1650} \times \frac{227.80}{223.19} \times \Phi_{p1} = 0.5258\Phi_{p1}$$

$$\frac{0.5258\Phi_{p1} - \Phi_{p1}}{\Phi_{p1}} \times 100 = \underline{-47.4\%}$$

10.13 DYNAMIC BEHAVIOR WHEN LOADING AND UNLOADING A DC MOTOR

Figure 10.13 illustrates the dynamic behavior of the speed, cemf, armature current, and developed torque when a constant-torque load is applied to the shaft of a shunt motor; the circled numbers indicate the sequence of events. With the motor running, and no load on the shaft, the developed torque just balances the friction, windage, and small stray load loss. Adding shaft load (at time t_1) causes $T_{load} > T_D$ and the armature slows down. The decrease in speed decreases the cemf, causing an increase in armature current and hence an increase in the developed torque. The machine continues to slow down, increasing its armature current and thus developing greater torque, until T_D becomes equal to the torque load on the shaft. When this occurs (time t_2), deceleration ceases and the machine operates at a lower steady-state speed and a higher armature current.

Similarly, if the shaft load is reduced, $T_D > T_{load}$, and the armature accelerates. As the speed increases, the increase in cemf causes the armature current to decrease, decreasing the developed torque. The machine continues to accelerate, decreasing its armature current, developing less and less torque, until $T_D = T_{load}$. When this occurs, there is no further acceleration, and the machine operates at a higher steady-state speed and a lower armature current.

When adding or removing load, the resultant unbalanced torque causes deceleration or acceleration, respectively. This change in speed, with its attendant lowering or raising of the cemf, automatically adjusts the current in a direction to balance the opposing torques.

10.14 SPEED REGULATION

The speed regulation of a direct-current motor is the percent change in speed from no load to rated load with respect to rated speed when operating at rated voltage and rated temperature from a constant-voltage source:

$$\text{SR} = \frac{n_{nl} - n_{rated}}{n_{rated}} \times 100 \text{ percent} \qquad \textbf{(10–20)}$$

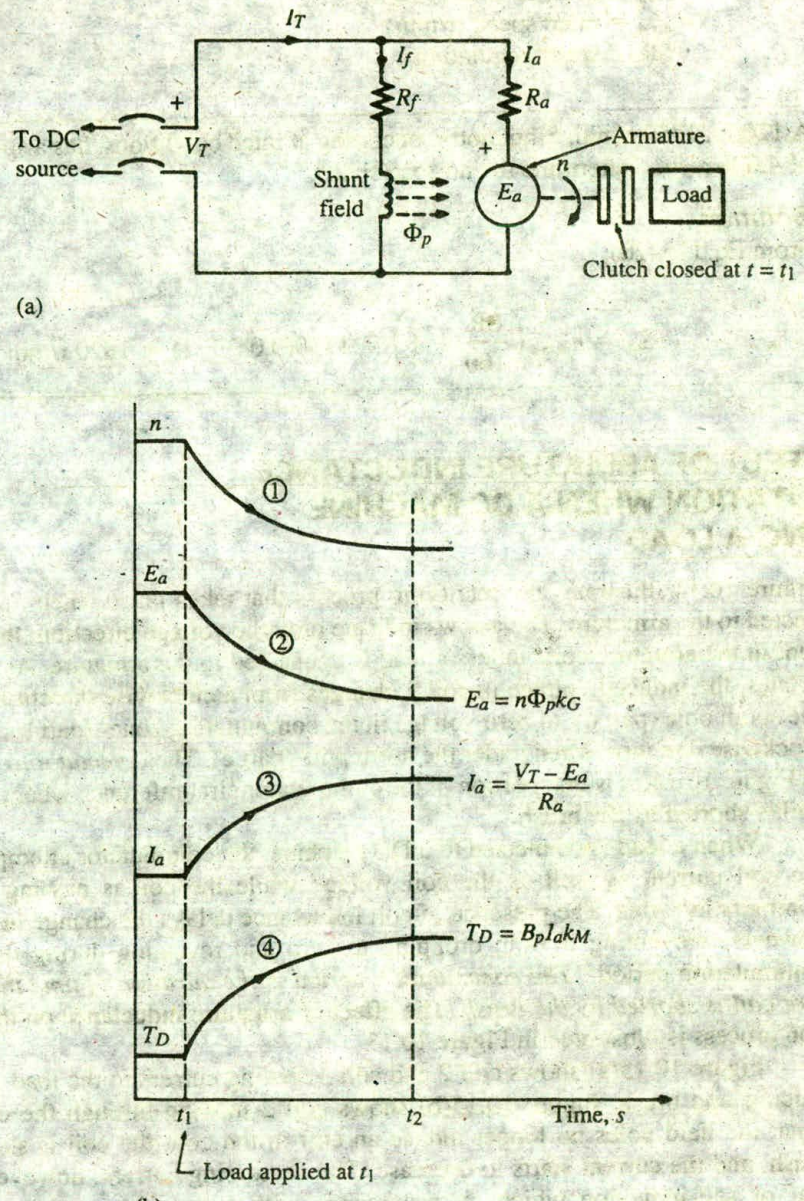


FIGURE 10.13
Dynamic behavior of a shunt motor when a constant-torque load is applied to the shaft: (a) equivalent circuit; (b) behavior of motor variables.

where: n_{nl} = no-load speed (r/min)
n_{rated} = rated speed (r/min)
SR = speed regulation

EXAMPLE 10.5 A 120-V, 1750 r/min, 5-hp motor, operating at rated conditions, has a speed regulation of 4.0 percent. Determine the no-load speed.

Solution
From Eq. (10–20),

$$S_{nl} = n_{rated}\left(\frac{SR}{100} + 1\right) = 1750(0.04 + 1) = \underline{1820 \text{ r/min}}$$

10.15 EFFECT OF ARMATURE INDUCTANCE ON COMMUTATION WHEN A DC MACHINE IS SUPPLYING A LOAD

Figure 10:14 illustrates the rectifying process that takes place when no load is connected to the armature. The arrows indicate only the voltage direction; there is no current in the armature coils unless a load is connected to the armature. As the armature rotates, the induced voltage in coil 2 changes from a clockwise direction when under the south pole (part a), to zero voltage in the commutating zone[5] (part b), to a counterclockwise direction when under the north pole (part c). The *commutating zone,* shown in Figure 10.14(a) is that portion of the commutator circumference where the armature coil is shorted by the brush.

When a load is connected to a DC machine, the commutator attempts to reverse the coil current as well as the coil voltage while the coil is passing through the commutation zone. The presence of coil inductance delays the change in coil current, however, preventing it from dropping to zero and reversing during the very brief commutation period.[6] *The commutation period is the duration of time that the armature coil is shorted by the brush.* The effect of armature inductance on the commutation process is illustrated in Figure 10.15.

Figure 10.15(a) shows coil 2 and coil 3 feeding current to the load via the commutator and brush. Figure 10.15(b) shows coil 2 moving through the commutating zone; the field poles no longer induce an emf in the coil, the coil is shorted by the brush, and the current starts to decrease. The decreasing current, however, causes an emf of self-induction which, in accordance with Lenz's law, delays the change. Hence, coil 2 rotates into the position shown in Figure 10.15(c) without having had sufficient time for its current to drop to zero. As commutator bar 3 slides off the brush,

[5]Any voltage produced by flux fringing into the commutation zone at no load is insignificant.

[6]If each pair of armature slots contains more than one coil, the inductive effect is increased by mutual inductance between the coils.

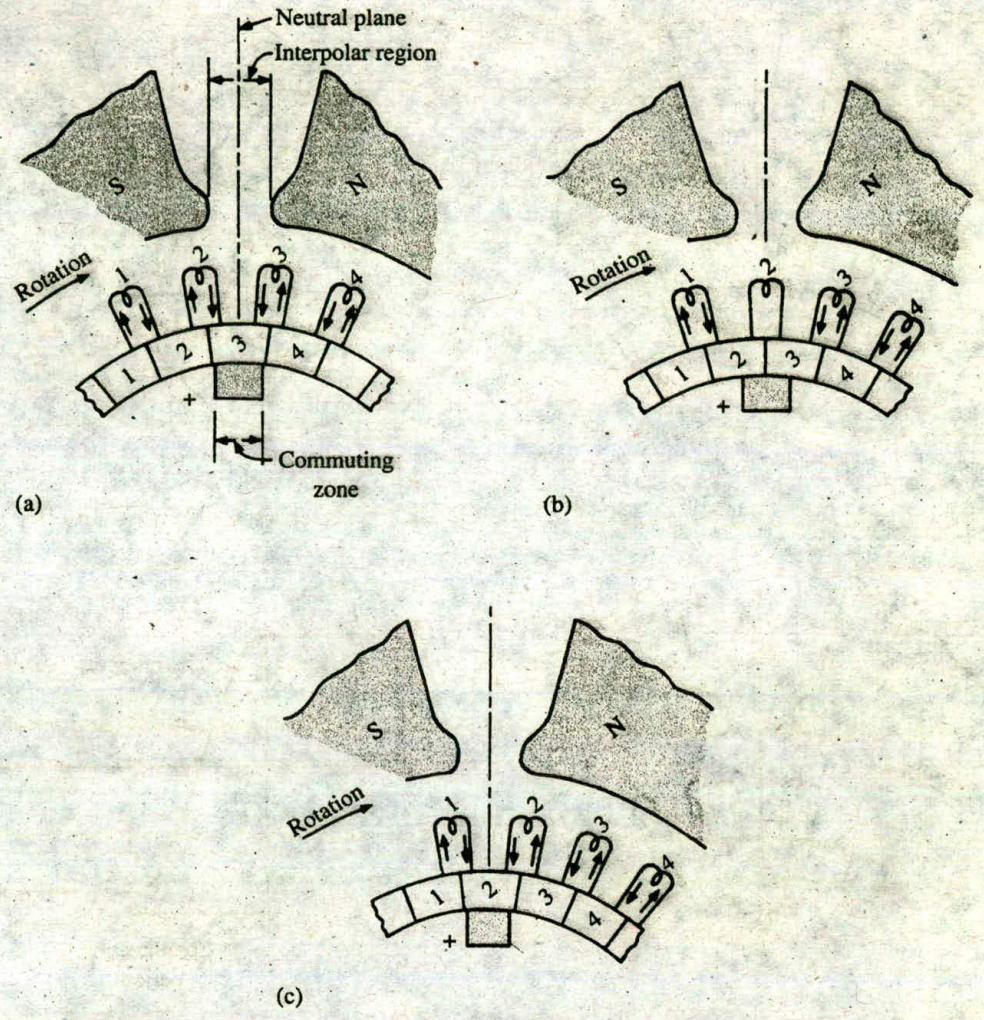


FIGURE 10.14
Commutation process under no-load conditions. The sequence of sketches shows the reversal of voltage in coil 2 as it enters and leaves the commutating zone.

the current in coil 2 is suddenly forced to zero, generating a high emf of self-induction that causes an arc to jump between commutator bar 3 and the brush. If allowed to continue, such arcing will severely damage both the commutator and the brushes, making it impossible to operate the machine unless corrective measures are taken.

Successful operation of a DC machine requires that during the very brief commutation period the coil current reverses from full value in one direction to full value in the opposite direction. Ideal commutation occurs when the current changes direction midway through the commutation period, as shown in Figure 10.15(d). Thus for ideal commutation, the coil current will be in phase with the coil voltage.

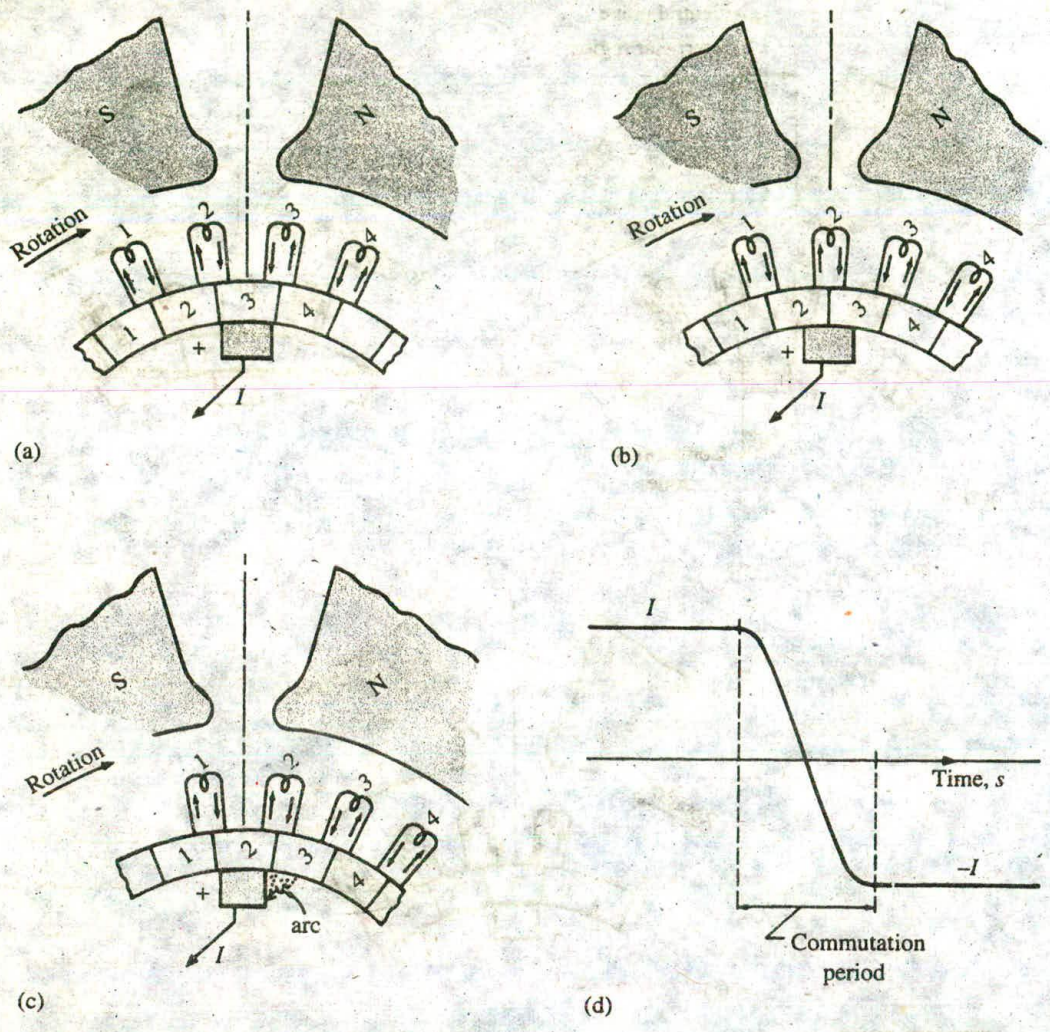


FIGURE 10.15
Commutation process under load conditions: (a), (b), and (c) show delay in current reversal and resultant arc caused by coil inductance; (d) graph of ideal commutation.

10.16 INTERPOLES

To eliminate sparking caused by the emf of self-induction, narrow poles called *interpoles* or *commutating poles* are installed in the neutral plane of DC machines. The interpoles, shown in the cutaway view of a DC machine in Figure 10.6, affect only the coil undergoing commutation. The interpole windings are designed to generate a neutralizing voltage of sufficient magnitude to force the reversal of current in each armature coil as it moves through the interpolar region. Ideally, the current in the coil undergoing commutation should start decreasing when it enters the commutating

zone, become zero when in the neutral plane, and then rise in the opposite direction, reaching full value at the moment it leaves the commutating zone.

The interpole windings are connected in series with the armature, as shown in Figure 10.16 for an elementary machine, so that their strength will be proportional to the armature current. The interpole winding forms part of the armature circuit and should not be disconnected or reversed. Incorrect connections will result in worse sparking than if no interpoles were used. The polarity of the interpoles with respect to the polarity of the field poles is shown in Figure 10.16 for the specific direction of rotation, for both motors and generators.

Since an armature coil spans approximately 180 electrical degrees, both sides of the coil will enter the magnetic neutral plane at the same time. Hence, instead of using two interpoles to induce a neutralizing voltage in each coil as it enters the neutral plane, one interpole with more turns may be used.

Interpole Saturation

When operating at rated load or below, the interpole flux remains in proportion to the armature current, and as a result, the neutralizing emf will always be equal and opposite to the emf of self-induction. When operating well above rated load, however, the interpole iron saturates, and its flux is no longer proportional to the armature current. The interpole can no longer generate an opposing emf in proportion to the emf of self-induction, and a relatively large current will appear in the coils short circuited by the brushes, causing sparking.

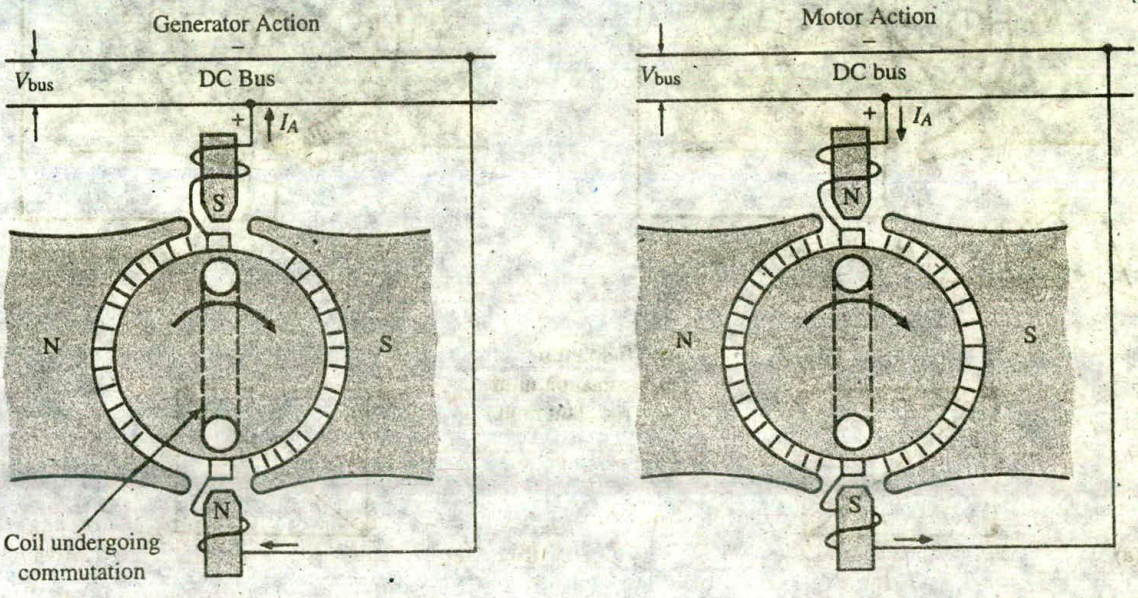


FIGURE 10.16
Location of interpoles, their connections, and their polarity for generators and motors.

10.17 ARMATURE REACTION

When a generator or motor is loaded, the current in the armature coils develops a magnetomotive force of its own that interacts with the magnetomotive force of the field poles, disturbing the uniform flux distribution in the air gap. This behavior is called armature reaction.

The effect of armature reaction on the flux distribution is shown in Figure 10.17(a) for generator action and in Figure 10.17(b) for motor action. The accompanying vector diagrams are useful only for showing the direction of flux shift due to the respective armature mmfs. Although only one armature coil is shown in Figure 10.17, the many coils of a practical machine are distributed uniformly around the armature as previously shown in Figure 10.7. Thus, when an armature coil rotates from the position shown in Figure 10.17, another coil takes its place, and the armature mmf remains fixed in space.

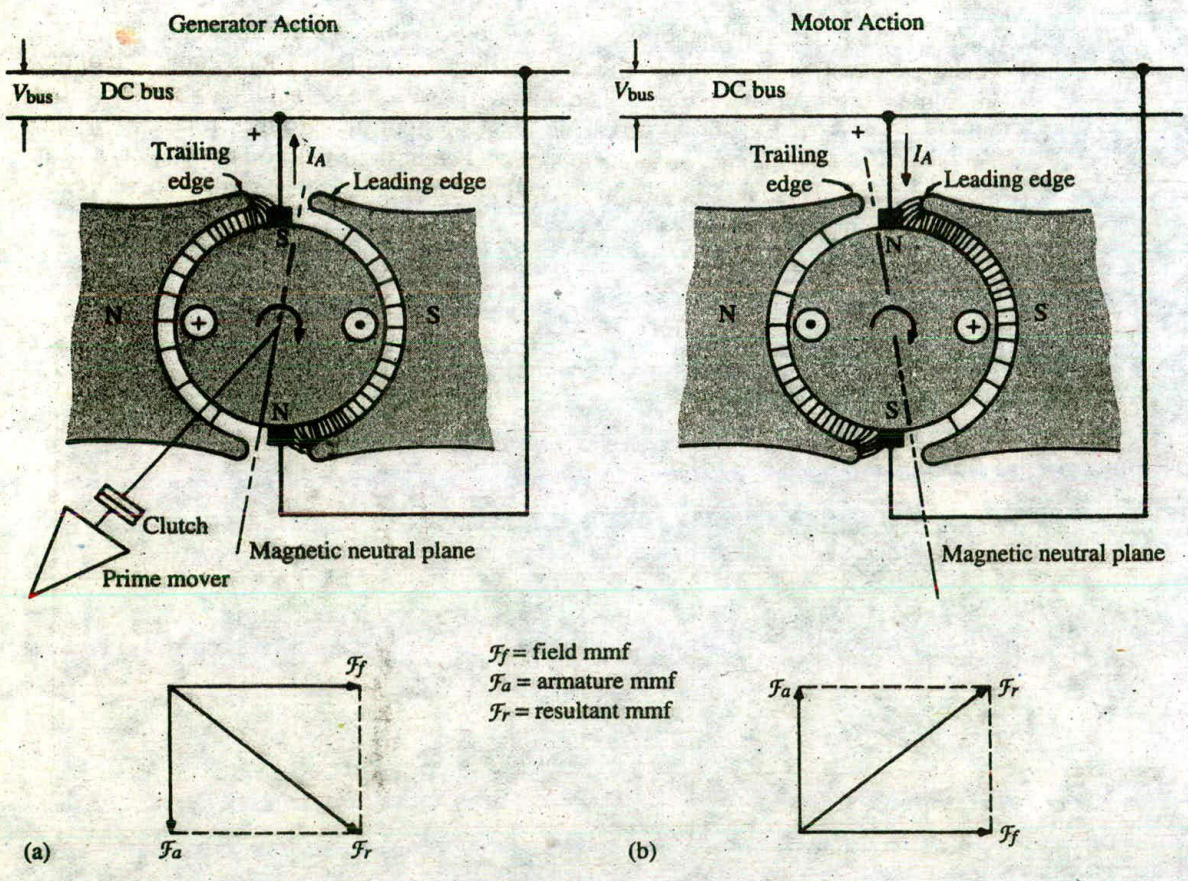


FIGURE 10.17
Effect of armature reaction in DC generators and motors. Note leakage of flux into interpolar region.

Armature Reaction in a DC Generator

As shown in Figure 10.17(a), the armature reaction mmf in a generator causes the neutral plane to shift its axis in the direction of rotation. The net result is an increase in flux at the *trailing edges* of the poles, a decrease in flux at the leading edges,[7] and some flux fringing into the interpolar region. Because of the nonlinear nature of the pole iron, however, the increase in flux at the trailing edges is less than the decrease in flux at the leading edges, resulting in a net reduction in total pole flux. *Although the resultant mmf vector $\mathcal{F}_r$ shown in Figure 10.17 indicates an increase in magnetization, the shift of the flux axis due to the armature mmf, combined with magnetic saturation, results in a demagnetizing effect.*

Armature reaction has two adverse effects on the performance of a DC generator:

1. Flux in the interpolar region causes a voltage to be generated in the coil undergoing commutation, causing arcing at the brushes.
2. The net reduction in total pole flux results in an undesirable reduction in generated voltage.

Armature Reaction in a Motor

As shown in Figure 10.17(b), the armature reaction mmf in a motor causes the neutral plane to shift its axis in a direction opposite to the direction of rotation. The net result is an increase in flux at the *leading edges* of the poles, a decrease in flux at the trailing edges, and some fringing of flux into the interpolar region. This has two adverse effects on the performance of a DC motor:

1. Flux in the interpolar region causes a voltage to be generated in the coil undergoing commutation, causing arcing at the brushes.
2. The net reduction in total pole flux results in an undesirable increase in motor speed.

Armature Reaction and Interpoles

The degree to which armature reaction affects the performance of a DC machine, whether as a motor or as a generator, is dependent on the magnitude of the armature current. Increased loading increases the armature mmf, thus increasing the adverse effects.

If the interpoles are made sufficiently strong by the addition of more turns, they will produce additional opposing mmf to nullify the effect of the armature mmf in the interpolar region and yet remain equally effective in opposing the emf of self-induction in the coils undergoing commutation. Although they do eliminate or reduce sparking, interpoles do not prevent the shift of flux across the pole face brought about by armature reaction; they merely prevent flux from fringing into the interpolar region. The total field flux is still reduced by saturation at the respective pole tips.

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[7]When an armature conductor enters the interpolar region, it departs from the trailing edge and approaches the leading edge.

Net Flux in the Air Gap of a DC Machine

The net flux in the air gap of a DC machine (motor or generator) can be expressed in terms of the field mmf and an *equivalent demagnetizing mmf* caused by armature reaction. Expressed in equation form,

$$\mathcal{F}_{net} = \mathcal{F}_f - \mathcal{F}_d \tag{10–21}$$

$$\Phi_{gap} = \frac{\mathcal{F}_{net}}{\mathcal{R}} \tag{10–22}$$

where: $\mathcal{F}_{net}$ = net mmf (A-t/pole)
$\mathcal{F}_f$ = field mmf (A-t/pole)
$\mathcal{F}_d$ = equivalent demagnetizing mmf (A-t/pole)
$\mathcal{R}$ = reluctance (nonlinear)

Note: Although not exact, $\mathcal{F}_d$ is assumed proportional to the armature current. However, if a compensating winding (as described in Section 10.19) is used $\mathcal{F}_d = 0$.

10.18 BRUSH SHIFTING AS AN EMERGENCY MEASURE

The brush-neutral setting should not be changed to minimize sparking unless reasonable evidence indicates an incorrect setting.[8] The most likely causes of sparking at the brushes are an open coil in the armature, defective interpoles, incorrect brush-spring pressure, or wrong brush grade. An incorrect neutral setting may occur as a result of improper assembly after overhaul, or commutator wear. A commutator whose diameter was reduced by excessive wear and resurfacing may cause the brushes to contact the commutator at a slightly off-neutral position.

If the interpoles are defective, and repair or replacement requires an unacceptable downtime, shifting the brush rigging in the direction of rotation for a generator, and against the direction of rotation for a motor, will reduce sparking. Since the angular shift of flux caused by armature reaction is a function of the magnitude of the armature current, however, the brushes would have to be shifted to a different position for each value of load.[9]

Furthermore, shifting the brushes causes the armature mmf to have a component in a direction that weakens the field flux. This is illustrated in Figure 10.18 for a DC *generator*. The *normal position* of the brushes, shown in Figure 10.18(a), results in the armature mmf $\mathcal{F}_a$ to be normal to the field mmf $\mathcal{F}_f$. Shifting the brushes to the position shown in Figure 10.18(b) causes a component of armature mmf ($\mathcal{F}_d$) to be in opposition to the field mmf.

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[8] See Reference [1] for more information on brush sparking and for test procedures to locate the correct brush-neutral setting.

[9] Before interpoles were invented, a brush-shifting lever was mounted on the brush rigging to provide for easy shifting of the brush axis as load came on and off.

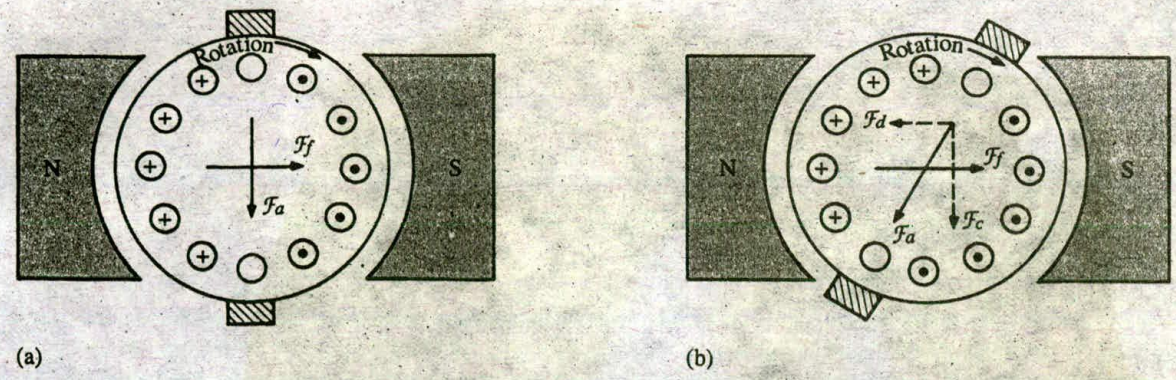


FIGURE 10.18
Effect of brush shift on the strength of the magnetic field of a DC generator: (a) brushes in magnetic-neutral plane; (b) brushes shifted to a new position in the direction of rotation.

Brush shifting should be done only as a last resort, and the brush rigging should be positioned to reduce sparking when operated at the average load. This is an extremely critical task that should be done by competent motor mechanics. If done incorrectly, injury to operating personnel and damage to equipment could occur.

10.19 COMPENSATING WINDINGS

The effect of armature reaction is particularly severe in applications where quick reversals and/or large and rapid load changes occur. Sudden large changes in armature flux induce high transient voltages in all armature coils by transformer action. If the transient voltages are high enough to cause arcing between commutator bars, a brush-to-brush flashover may occur. A *flashover* is a transient high-current arc accompanied by a loud explosive noise. Minor flashovers cause pitting of the commutator bars and burned spots on the edges of the brushes. A severe flashover may melt brush holders and commutator bars, as well as damage the armature winding and core. To prevent flashovers, DC machines designed for large and rapid load swings, such as in steel mills and ship propulsion, are equipped with *pole-face windings.* The pole-face winding, called a *compensating winding,* is shown in Figure 10.19. The compensating winding is connected in series with the armature, and essentially *eliminates armature reaction by setting up a mmf that is always equal and opposite to the armature mmf.*

Figure 10.20 illustrates the parallel arrangement of conductors and the relative directions of current in the armature and in the compensating winding (CW) for a one-coil elementary machine (generator and motor); the accompanying vector diagram shows the component mmf vectors. The compensating winding acts as a large coil surrounding the armature and connected in series with it.

Note that machines with compensating windings still require interpoles to counteract the emf of self-induction in the coils undergoing commutation.

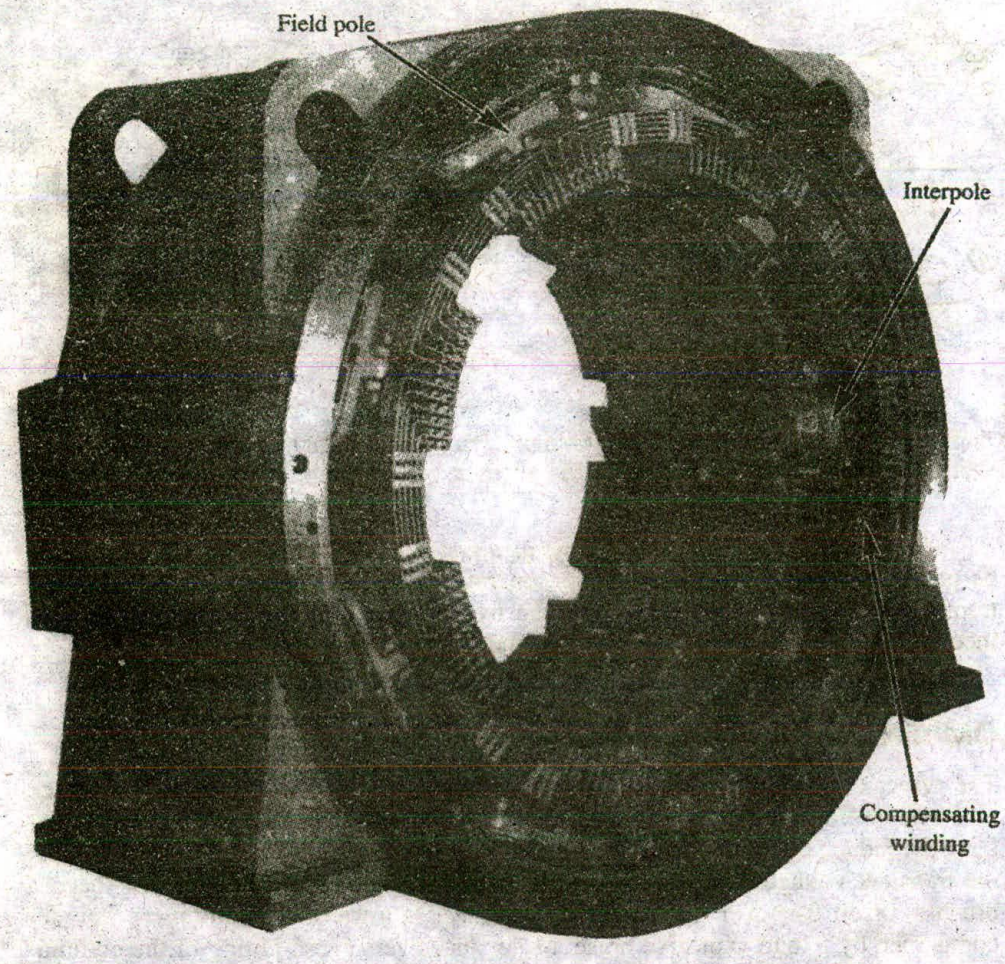


FIGURE 10.19
Direct-current machine with interpoles and compensating windings. (Courtesy Reliance Electric Company)

10.20 COMPLETE EQUIVALENT CIRCUIT OF A SEPARATELY EXCITED SHUNT GENERATOR

The complete equivalent-circuit diagram of a separately excited shunt generator that includes interpoles and compensating windings is shown in Figure 10.21. Applying Kirchhoff's voltage law to the armature circuit, and assuming steady-state conditions,

$$E_a = I_a R_{\text{acir}} + V_T \tag{10–23}$$

Defining:

$$R_{\text{acir}} = R_a + R_{\text{IP}} + R_{\text{CW}} \tag{10–24}$$

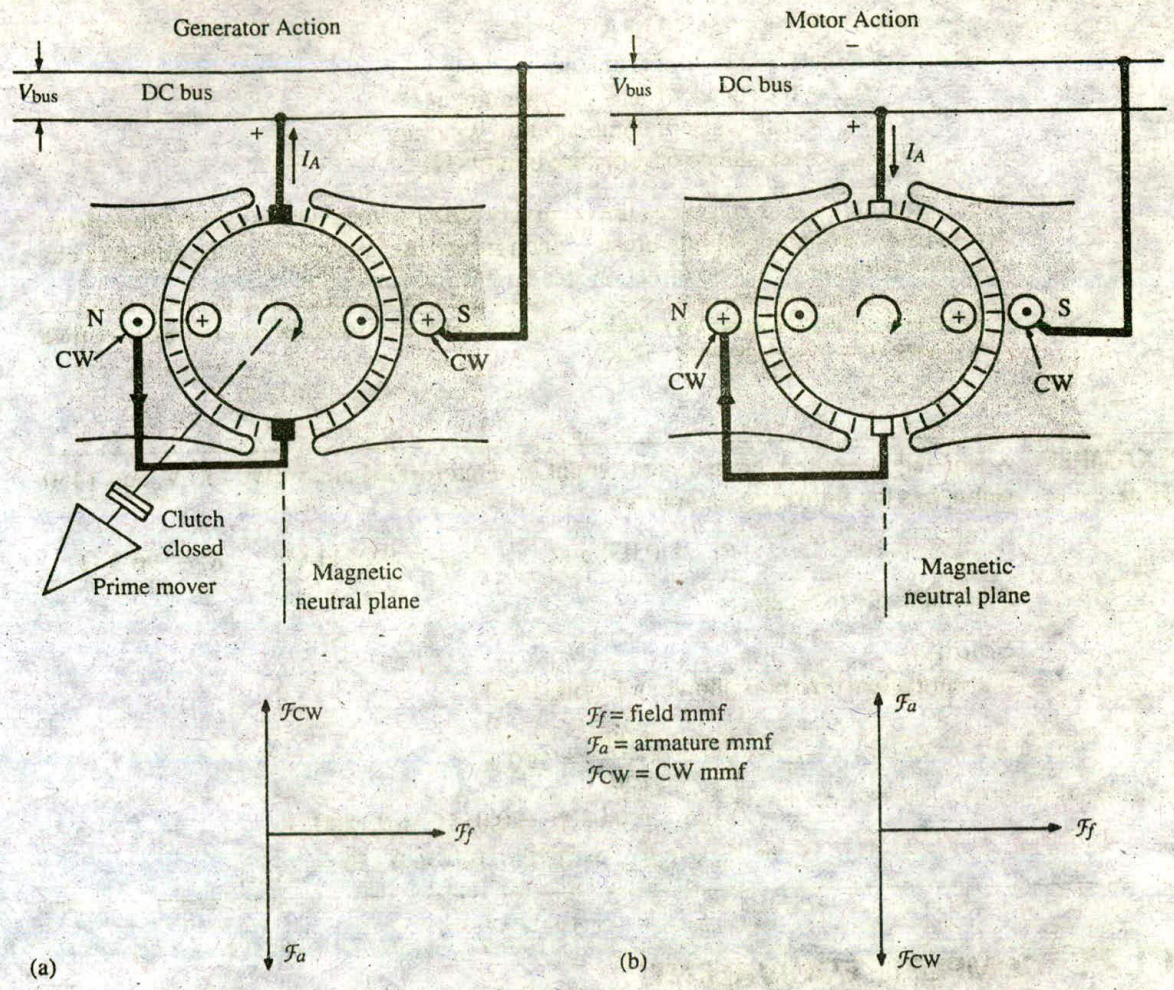
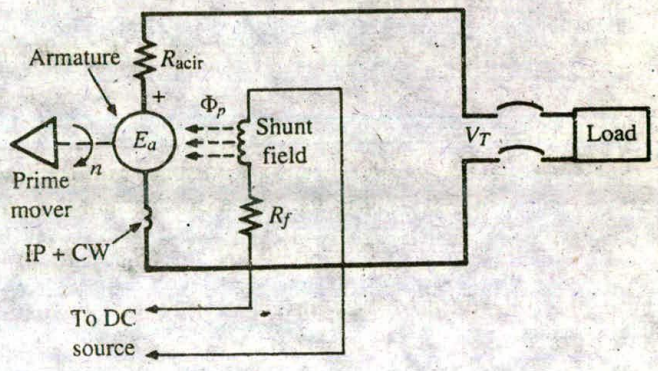


FIGURE 10.20
Elementary diagram showing parallel arrangement of conductors and relative directions of current in armature and compensating winding for (a) generators; (b) motors.

FIGURE 10.21
Complete equivalent circuit of a separately excited shunt generator that includes interpoles and compensating windings.



where: R_a = resistance of armature windings (Ω)
R_{IP} = resistance of interpole windings (Ω)
R_{CW} = resistance of compensating windings (Ω)
R_{acir} = resistance of armature circuit (Ω)

Note: Equation (10–23) ignores the relatively small voltage drop (called *brush drop*) across each carbon or graphite brush,[10] and ignores the inductance of the armature circuit. The inductance has no effect on steady-state performance.

[10]The brush drop cannot be ignored when determining losses. See Section 10.26. For more information on brush materials and brush drop, see References [2],[3].

EXAMPLE 10.6 A separately excited, compensated shunt generator, rated at 25 kW, 250 V, and 1450 r/min, has the following parameters;

$R_a = 0.1053\ \Omega$ $R_{IP} = 0.0306\ \Omega$ $R_{CW} = 0.0141\ \Omega$ $R_f = 96.3\ \Omega$

Determine the induced emf.

Solution

The equivalent circuit is shown in Figure 10.21.

$$I_a = \frac{P}{V_T} = \frac{25{,}000}{250} = 100\text{ A}$$

$$R_{acir} = 0.1053 + 0.0306 + 0.0141 = 0.1500\ \Omega$$

$$E_a = V_T + I_a R_{acir} = 250 + 100 \times 0.150 = \underline{265\text{ V}}$$

10.21 COMPLETE EQUIVALENT CIRCUIT OF A SHUNT MOTOR

The complete equivalent-circuit diagram of a shunt motor that includes interpoles and compensating windings is shown in Figure 10.22.

Applying Kirchhoff's voltage law to the armature circuit, and assuming steady-state conditions,

$$V_T = E_a + I_a R_{acir}$$

$$E_a = V_T - I_a R_{acir} \qquad \textbf{(10–25)}$$

EXAMPLE 10.7 A 30-hp, 500-V, 850 r/min shunt motor draws a line current of 51.0 A when operating at rated conditions. The motor parameters are

$R_a = 0.602\ \Omega$ $(R_{IP} + R_{CW}) = 0.201\ \Omega$ $R_f = 408.5\ \Omega$

Determine the cemf.

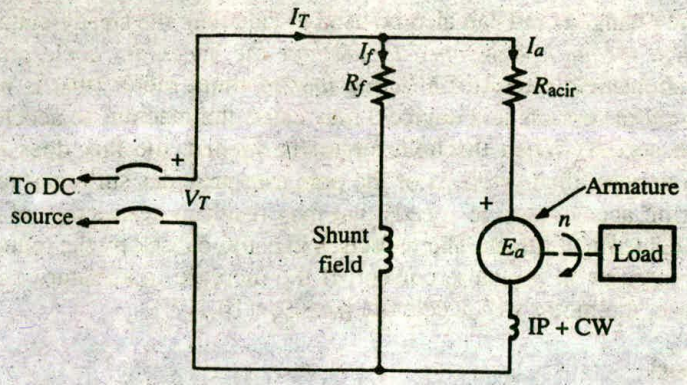


FIGURE 10.22
Complete equivalent circuit of a shunt motor that includes interpoles and compensating windings.

Solution
The equivalent circuit is similar to that shown in Figure 10.22.

$$I_f = \frac{V_T}{R_f} = \frac{500}{408.5} = 1.224 \text{ A}$$

$$I_a = I_T - I_f = 51.0 - 1.224 = 49.78 \text{ A}$$

$$R_{acir} = R_a + (R_{IP} + R_{CW}) = 0.602 + 0.201 = 0.803\ \Omega$$

$$E_a = V_T - I_a R_{acir} = 500 - 49.78 \times 0.803 = \underline{460.0 \text{ V}}$$

10.22 GENERAL SPEED EQUATION FOR A DC MOTOR

The general speed equation for a DC motor is obtained by substituting Kirchhoff's voltage equation for the armature circuit into the basic speed equation. From Eq. (10–19)

$$n = \left.\frac{E_a}{\Phi_p k_G}\right|_{\Phi_p \neq 0}$$

Substituting Eq. (10–25) into Eq. (10–19),

$$n = \left.\frac{V_T - I_a R_{acir}}{\Phi_p k_G}\right|_{\Phi_p \neq 0} \text{ r/min} \qquad \textbf{(10–26)}$$

where:
R_{acir} = armature-circuit resistance (Ω)
I_a = armature current (A)
k_G = constant
n = speed (r/min)
Φ_p = flux produced by shunt field winding (Wb)

Motor speed Eq. (10–26) indicates the general trend of speed when the various parameters are changed, and can also be used to calculate the steady-state speed, *providing sufficient torque is developed to produce the necessary accleration. Note:* A break in the shunt-field circuit of a *lightly loaded* shunt motor (that is not protected with overcurrent or loss-of-field devices) may cause the machine to accelerate to dangerously high speeds. When the field circuit is opened, the flux does not instantaneously drop to zero; the hysteresis of the pole iron provides sufficient residual magnetism to permit acceleration to speeds that may result in destruction of the machine by excessive centrifugal forces. The reduction in cemf, caused by the reduction in flux, results in an increase in armature current. If the increase in armature current causes $B_p I_a$ to increase, the motor will accelerate [see Eq. (10–17)].

Base Speed

The base speed of a direct-current motor is its nameplate value, and is the speed obtained at rated voltage, rated shaft load, rated operating temperature, and with no added resistance in series with the armature and/or in series with the shunt field.

To accelerate a machine above its base speed, the developed torque must be made greater than the load torque on the shaft plus the windage and friction torque. Similarly, to decrease the speed, the developed torque must be made less than the combined shaft load, friction, and windage. As indicated in Eq. (10–17), changes in developed torque require changes in the flux density and/or armature current.

EXAMPLE 10.8 A 25-hp, 240-V shunt motor operating at 850 r/min draws a line current of 91 A when operating at rated conditions. A 2.14-Ω resistor inserted in series with the armature causes the speed to drop to 634 r/min. The respective armature-circuit resistance and field-circuit resistance are 0.221 Ω and 120 Ω. Determine the new armature current.

Solution

The circuit diagram is shown in Figure 10.23.

$$I_f = \frac{240}{120} = 2\text{ A}$$

$$I_a = I_T - I_f = 91 - 2 = 89\text{ A}$$

Using Eq. (10–26), and noting that the shunt field current was not changed,

$$\frac{n_1}{n_2} = \frac{[V_T - I_{a1}R_{\text{acir}}]}{[V_T - I_{a2}(R_{\text{acir}} + R_x)]}$$

$$I_{a2} = \frac{\left[V_T - \dfrac{n_2}{n_1} \times (V_T - I_{a_1}R_{\text{acir}})\right]}{(R_{\text{acir}} + R_x)}$$

$$I_{a2} = \frac{\left[240 - \dfrac{634}{850} \times (240 - 89 \times 0.221)\right]}{(0.221 + 2.14)} = \underline{32.05\text{ A}}$$

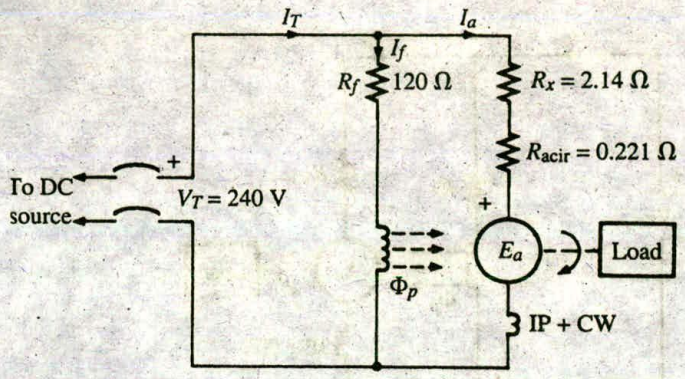


FIGURE 10.23
Circuit diagram for Example 10.8.

EXAMPLE 10.9 A shunt motor rated at 10 hp, 240 V, 2500 r/min, draws 37.5 A when operating at rated conditions. The motor parameters are $R_a = 0.213\ \Omega$, $R_{CW} = 0.065\ \Omega$, $R_{IP} = 0.092\ \Omega$, and $R_f = 160\ \Omega$. Determine (a) the steady-state armature current if a rheostat in the shunt field circuit reduces the flux in the air gap to 75.0 percent of its rated value, a 1.0-Ω resistor is placed in series with the armature, and the load torque on the shaft is reduced to 50 percent rated; (b) the steady-state speed for the conditions in (a).

Solution

The circuit diagram for rated conditions is shown in Figure 10.24(a).

(a) At rated conditions,

$$I_f = \frac{V_f}{R_f} = \frac{240}{160} = 1.50\ \text{A}$$

$$I_a = I_T - I_f = 37.5 - 1.5 = 36\ \text{A}$$

The circuit diagram for the new conditions is shown in Figure 10.24(b). From Eq. (10–17),

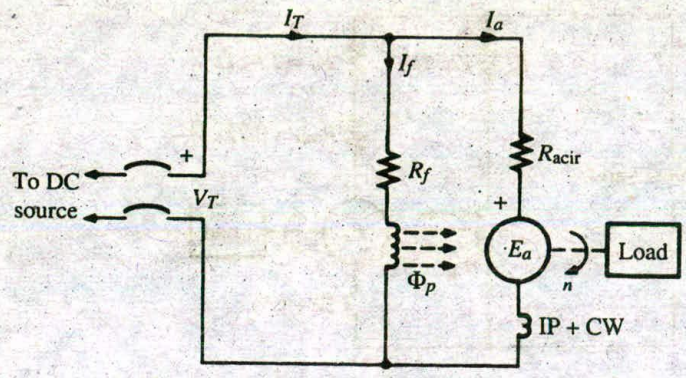
$$\frac{T_1}{T_2} = \frac{[\Phi_p I_a]_1}{[\Phi_p I_a]_2} \quad \Rightarrow \quad I_{a2} = I_{a1} \times \frac{T_2}{T_1} \times \frac{\Phi_{p1}}{\Phi_{p2}}$$

$$I_{a2} = 36 \times \frac{0.50\,T_1}{T_1} \times \frac{\Phi_{p1}}{0.75 \times \Phi_{p1}} = \underline{24.0\ \text{A}}$$

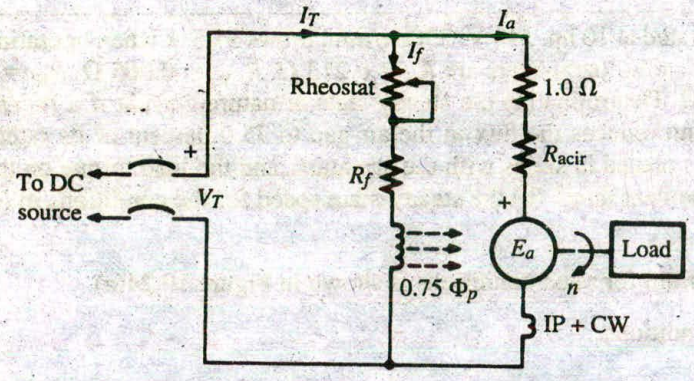
(b) $R_{acir} = R_a + R_{CW} + R_{IP} = 0.213 + 0.065 + 0.092 = 0.370\ \Omega$

From Eq. (10–26),

$$\frac{n_2}{n_1} = \left[\frac{V_T - I_a R_{acir}}{\Phi_p k_G}\right]_2 \times \left[\frac{\Phi_p k_G}{V_T = I_a R_{acir}}\right]_1$$



(a)



(b)

FIGURE 10.24
Circuit diagrams for Example 10.9: (a) rated conditions; (b) external resistor in series with the armature, and rheostat in series with the field.

$$n_2 = 2500 \times \left[\frac{240 - 24 \times (1 + 0.370)}{0.75\Phi_p k_G}\right] \times \left[\frac{\Phi_p k_G}{240 - 36 \times 0.370}\right]$$

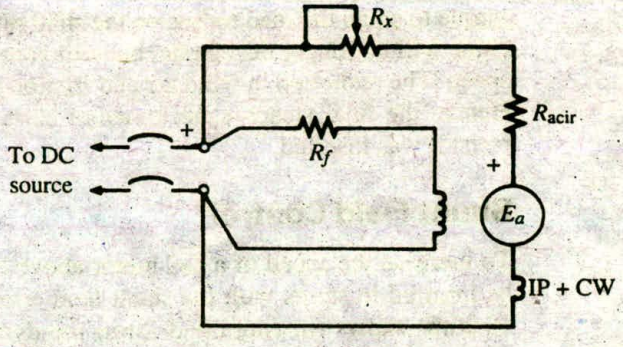
$$n_2 = \underline{3046 \text{ r/min}}$$

10.23 DYNAMIC BEHAVIOR DURING SPEED ADJUSTMENT

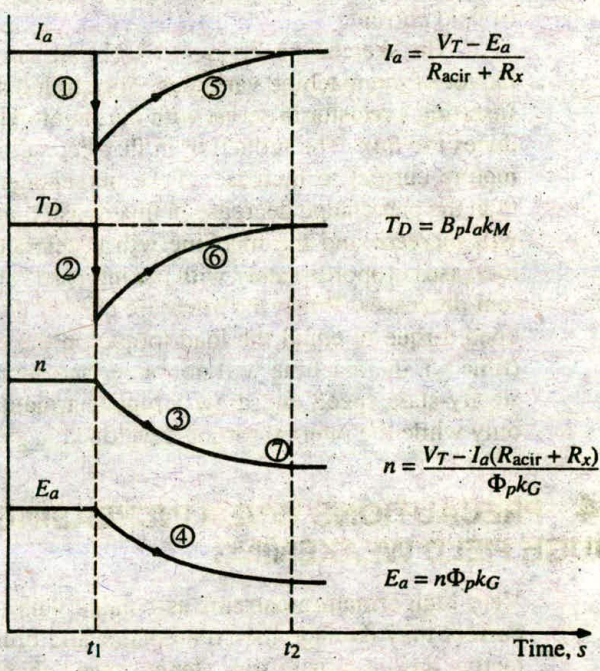
Armature Control

To reduce the speed of a DC motor below its base speed, a rheostat or resistor must be inserted in series with the armature as shown in Figure 10.25(a). Figure 10.25(b) shows the dynamic behavior of armature current, developed torque, speed, and cemf

FIGURE 10.25
(a) Circuit for speed adjustment below base speed; (b) dynamic behavior of motor variables.



(a)



Resistor Inserted at t_1

(b)

that occurs when a resistor is inserted in series with the armature of a shunt motor driving a constant-torque load. Although the sketches are not to scale, they do show the general behavior of the machine variables. The circled numbers indicate the sequence of events. Inserting a resistor in series with the armature causes a reduction in armature current that decreases the developed torque, and the machine slows down. As the machine decelerates, the cemf decreases, causing the newly reduced armature current to increase. When the armature current increases to a value that causes the developed

torque to equal the load torque on the shaft plus windage and friction (time t_2), the machine will no longer decelerate, but will continue to run at the new lower steady-state speed. The reduction in windage and friction due to the lower speed is relatively small. Hence, the final steady-state armature current is essentially the same as before the resistor was inserted.

Shunt Field Control

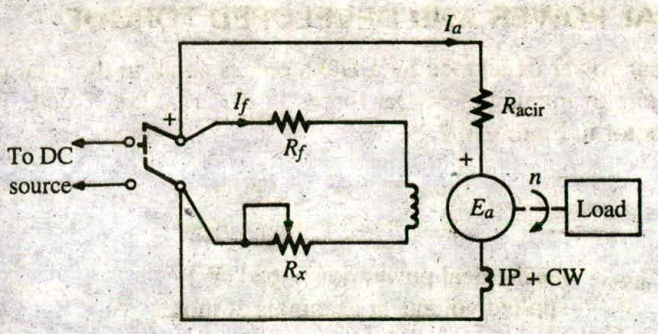
To increase the speed of a DC motor above its base speed, a resistor or rheostat must be inserted in series with the shunt field circuit, as shown in Figure 10.26(a). Figure 10.26(b) shows (in simplified form) the dynamic behavior of the field current flux, cemf, armature current, developed torque, and speed that occurs when a resistor is inserted in series with the shunt field of a shunt motor driving a constant-torque load. The inductive time constant of the shunt field circuit prevents an instantaneous change in field current.

The sketches in Figure 10.26(b) are not to scale, but do indicate the general behavior of the machine variables. The circled numbers indicate the sequence of events. Inserting a resistor in series with the shunt field decreases the field current and thus reduces the flux. The reduction in flux decreases the cemf, which in turn allows the armature current to increase. If the percentage increase in armature current is greater than the percentage decrease in flux density, and the flux density is not zero, the torque will increase and the machine will accelerate. As the machine accelerates, its cemf increases proportionately with the increased speed, and the newly raised armature current decreases. When the armature current decreases to a value that causes the developed torque to equal the load torque on the shaft plus the friction and windage load (time t_2), the machine will no longer accelerate but will continue to run at the higher steady-state speed and draw a higher armature current. The machine can accelerate only while the internal torque developed is greater than the load torque.

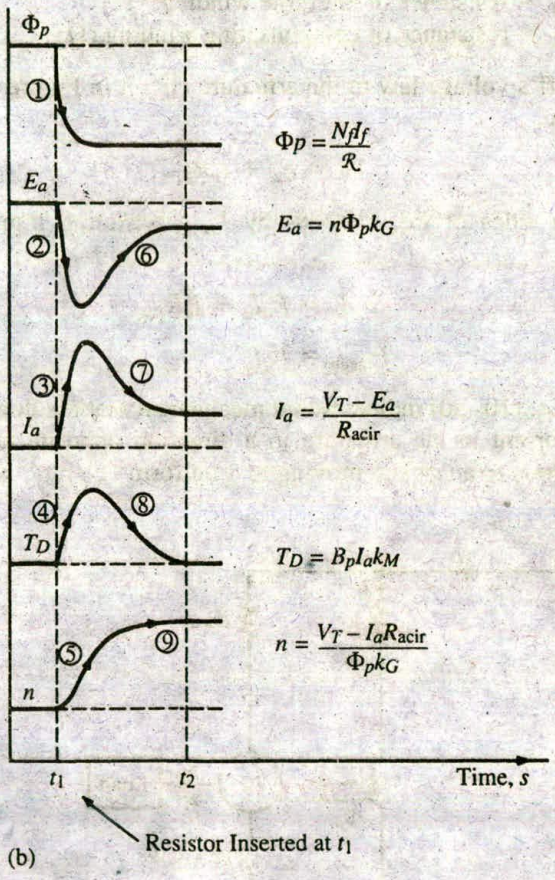
10.24 PRECAUTIONS WHEN INCREASING SPEED THROUGH FIELD WEAKENING

Very high armature currents associated with large and rapid reductions in shunt field current may damage the commutator and brushes if the circuit breaker or other protective device fails to trip. Hence, speed changes through shunt field rheostat control should be made slowly. Large high-inertia machines are more susceptible to damage than are small machines. Small machines can accelerate rapidly, permitting a quick buildup of cemf, and thus a rapid reduction in armature current.

Centrifugal stresses and commutation problems limit the maximum allowable speeds that may be safely attained by shunt field control. Ratings of direct-current motors for industrial service that are specifically designed for speed adjustment through field control are listed in NEMA tables. Direct-current motors that are not specifically designed for operation above base speed should not use shunt field control. Such machines are constructed to withstand an *emergency overspeed* equal to 25 percent of base speed for only 1 minute [4].



(a)



(b)

FIGURE 10.26
(a) Circuit for speed adjustment above base speed; (b) dynamic behavior of motor variables.

10.25 MECHANICAL POWER AND DEVELOPED TORQUE

The mechanical power developed by a DC motor is equal to the total power input to the armature circuit minus the copper losses in the armature circuit. Thus, referring to the shunt motor in Figure 10.27,

$$P_{\text{mech}} = V_T I_a - I_a^2 R_{\text{acir}} \qquad \textbf{(10–27)}$$
$$R_{\text{acir}} = R_a + R_{\text{IP}} + R_{\text{CW}}$$

where:
P_{mech} = mechanical power developed (W)
V_T = applied voltage at terminals of motor (V)
I_a = armature current (A)
R_{acir} = resistance of armature circuit (Ω)
R_a = resistance of armature windings (Ω)
R_{IP} = resistance of interpole windings (Ω)
R_{CW} = resistance of compensating winding (Ω)

Applying Kirchoff's voltage law to the armature circuit in Figure 10.27, and neglecting the brush drop,

$$V_T = E_a + I_a R_{\text{acir}} \qquad \textbf{(10–28)}$$

Multiplying both sides of Eq. (10–28) by I_a, substituting into Eq. (10–27), and simplifying,

$$V_T I_a = E_a I_a + I_a^2 R_{\text{acir}} \qquad \textbf{(10–29)}$$

$$P_{\text{mech}} = E_a I_a \qquad \textbf{(10–30)}$$

Examination of Eq. (10–30) indicates that mechanical work is done when the applied voltage causes current in the armature in a direction opposite to the cemf. This is somewhat analogous to an object moving at a uniform velocity, wherein the force of

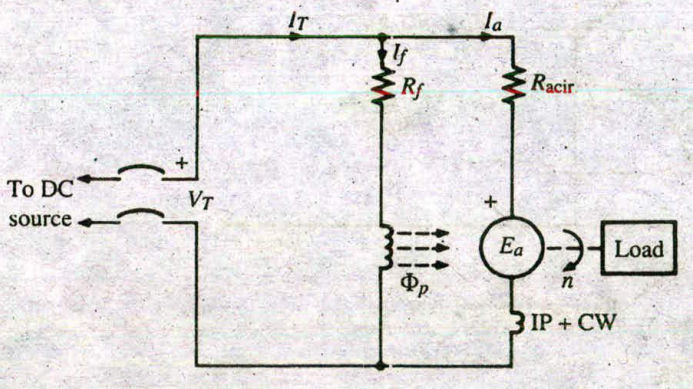


FIGURE 10.27
Circuit for derivation of mechanical power equation.

friction is equal and opposite to the applied force. Work is done by moving the object against the force of friction.

Motor Nameplates and NEMA

Motor nameplates and motor data supplied by manufacturers and the National Electrical Manufacturers Association (NEMA), are expressed in hp, r/min,[11] and lb-ft torque. Hence, these units will be used exclusively in all electric motor problems [4].

The basic equation that relates horsepower to developed torque and rotor speed is

$$P_{\text{mech}} = \frac{T_D n}{5252} \quad \text{hp} \tag{10–31}$$

where: T_D = developed torque (lb-ft)
n = shaft speed (r/min)

Converting Eq. (10–30) to horsepower, substituting into Eq. (10–31), and solving for torque,

$$P_{\text{mech}} = \frac{E_a I_a}{746} \quad \text{hp} \tag{10–32}$$

$$\frac{E_a I_a}{746} = \frac{T_D n}{5252}$$

$$T_D = \frac{7.04 E_a I_a}{n} \quad \text{lb-ft} \tag{10–33}$$

Note: Equation (10–33) applies only to running machines. If the machine stalls or is prevented from starting (locked rotor), the speed is zero, the cemf is zero, and Eq. (10–33) reduces to

$$T_D = \frac{0}{0}$$

which is indeterminate. Torque at blocked rotor must be determined from Eq. (10–17), where,

$$T_D \propto B_p I_a$$

The presence of armature current and pole flux is positive proof that torque is developed, even if the speed is zero.

[11] Nameplates on machines used in the United States indicate r/min as RPM.

EXAMPLE 10.10 A 40-hp, 240-V, 2500 r/min shunt motor operating at rated conditions has a line current of 140 A. The armature-circuit resistance and field-circuit resistance are 0.0873 Ω and 95.3 Ω, respectively. Determine (a) the mechanical power developed; (b) torque developed; (c) shaft torque.

Solution

The circuit is shown in Figure 10.27.

(a)
$$I_f = \frac{V_T}{R_f} = \frac{240}{95.3} = 2.52 \text{ A}$$
$$I_a = I_T - I_f = 140 - 2.52 = 137.48 \text{ A}$$

From Kirchhoff's voltage law applied to the armature circuit,

$$E_a = V_T - I_a R_{\text{acir}} = 240 - 137.48 \times 0.0873 = 228.0 \text{ V}$$
$$P_{\text{mech}} = E_a I_a = 228.0 \times 137.48 = \underline{31{,}345 \text{ W}}$$
$$P_{\text{mech}} = \frac{E_a I_a}{746} = \frac{31{,}345}{746} = \underline{42.0 \text{ hp}}$$

(b)
$$T_D = \frac{7.04 E_a I_a}{n} = \frac{7.04 \times 31{,}345}{2500} = \underline{88.3 \text{ lb-ft}}$$

(c)
$$P = \frac{Tn}{5252} \quad \Rightarrow \quad T = \frac{P \times 5252}{n}$$
$$T_{\text{shaft}} = \frac{40 \times 5252}{2500} = \underline{84.0 \text{ lb-ft}}$$

10.26 LOSSES AND EFFICIENCY

Power-flow diagrams that illustrate the flow of power through a direct-current motor and a direct-current generator are shown in Figures 10.28(a) and (b), respectively. As indicated in the diagrams, the total power loss for the machine, whether operating as a generator or as a motor, is

$$P_{\text{loss}} = P_{\text{acir}} + P_b + P_{\text{core}} + P_{\text{fcl}} + P_{f,w} + P_{\text{stray}}$$
$$P_b = V_b I_a \qquad \textbf{(10–34)}$$

where:
P_{acir} = armature-circuit loss ($I_a^2 R_{\text{acir}}$), (W)
P_b = brush-contact loss (W)
P_{fcl} = field-circuit loss ($I_f^2 R_f$) (W)
P_{core} = core loss (W)
$P_{f,w}$ = friction and windage loss (W)
P_{stray} = stray-load loss (W)
V_b = brush-contact drop (V)

The core loss is the combined hysteresis and eddy-current losses in the armature and field iron. The stray-load loss includes losses in the coils undergoing commutation and losses due to eddy currents in the copper that are not accounted for in the calculated $I_a^2 R_a$ of the armature. Stray-load losses are approximately equal to 1 percent of the output power **[2]**.

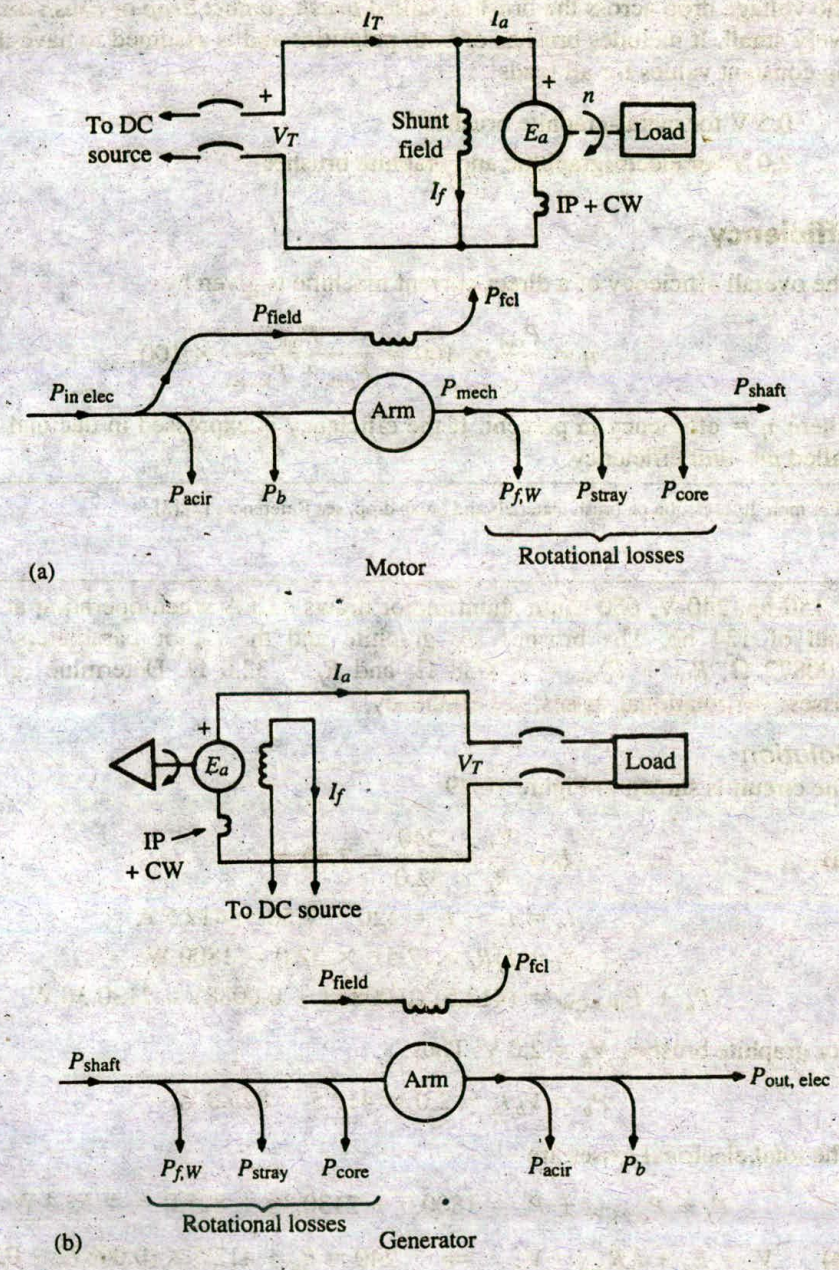


FIGURE 10.28
Power-flow diagrams: (a) shunt motor; (b) separately excited shunt generator.

Brush-Contact Drop

The voltage drop across the brushes, called *brush-contact drop* or *brush drop,* is relatively small. It includes brushes of both polarities and is assumed to have the following constant values for all loads[12]:

0.5 V for metal-graphite brushes

2.0 V for electrographitic and graphite brushes

Efficiency

The overall efficiency of a direct-current machine is given by

$$\eta = \frac{P_{out}}{P_{in}} \times 100 = \frac{P_{out}}{P_{out} + P_{losses}} \times 100 \qquad \textbf{(10–35)}$$

where η = efficiency in percent. If the efficiency is expressed in decimal form, it is called *per-unit* efficiency.

[12]For more information on brush materials and brush drop, see References [2],[3].

EXAMPLE 10.11 A 150-hp, 240-V, 650 r/min shunt motor draws 420 A when operating at a reduced load of 124 hp. The brushes are graphite and the motor parameters are R_a = 0.00872 Ω, $R_{IP} + R_{CW}$ = 0.0038 Ω, and R_f = 32.0 Ω. Determine (a) electrical losses; (b) rotational losses; (c) efficiency.

Solution

The circuit is shown in Figure 10.29.

(a)

$$I_f = \frac{V_T}{R_f} = \frac{240}{32.0} = 7.50 \text{ A}$$

$$I_a = I_T - I_f = 420 - 7.50 = 412.5 \text{ A}$$

$$P_f = I_f^2 R_f = (7.5)^2 \times 32.0 = 1800 \text{ W}$$

$$P_a + P_{IP+CW} = (412.5)^2(0.00872 + 0.0038) = 2130.36 \text{ W}$$

For graphite brushes, V_b = 2.0 V. Thus,

$$P_b = V_b I_a = 2.0 \times 412.5 = 825.0 \text{ W}$$

The total electrical losses are

$$P_f + P_{a+CW} + P_b = 1800.0 + 2130.36 + 825.0 = \underline{4755.4 \text{ W}}$$

(b) $V_T = E_a + I_a R_{acir} + V_b \quad \Rightarrow \quad 240 = E_a + 412.5 \times (0.00872 + 0.0038) + 2$

$$E_a = 232.835 \text{ V}$$

$$P_{mech} = E_a I_a = 232.835 \times 412.5 = 96{,}044 \text{ W}$$

$$P_{shaft} = 124 \times 746 = 92{,}504 \text{ W}$$

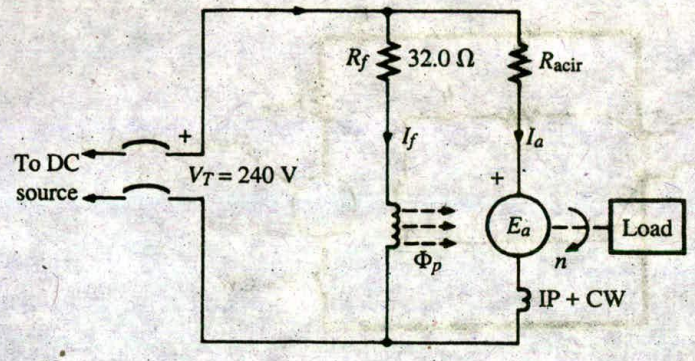


FIGURE 10.29
Circuit for Example 10.11.

From Figure 10.28(a),

$$P_{\text{rotational}} = P_{\text{mech}} - P_{\text{shaft}} = 96{,}044 - 92{,}504 = \underline{3540\ \text{W}}$$

(c)
$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{92{,}504}{420 \times 240} \times 100 = \underline{91.8\%}$$

Alternatively,

$$\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{losses}}} = \frac{92{,}504}{92{,}504 + 3540 + 4755.4} \times 100 = \underline{91.8\%}$$

10.27 STARTING A DC MOTOR

When voltage is applied to a motor, the combined inertia of the motor and shaft load prevent instant rotation. The effect is the same as though the rotor were physically blocked. The values of current and developed torque that occur under these conditions are called the *blocked-rotor* or *locked-rotor* values.

The current drawn by the armature in Figure 10.30 is

$$I_a = \frac{V_T - E_a}{R_{\text{acir}}} \tag{10–36}$$

At locked-rotor conditions, however, the speed is zero. Hence, the cemf is zero and the current at locked rotor is

$$I_{a,\text{lr}} = \frac{V_T - 0}{R_{\text{acir}}} = \frac{V_T}{R_{\text{acir}}} \tag{10–37}$$

where $I_{a,\text{lr}}$ = armature current at locked rotor (A). To minimize copper losses, and hence increase efficiency, the armature is wound with conductors of relatively large cross section. Hence, to prevent excessively high armature currents when starting,

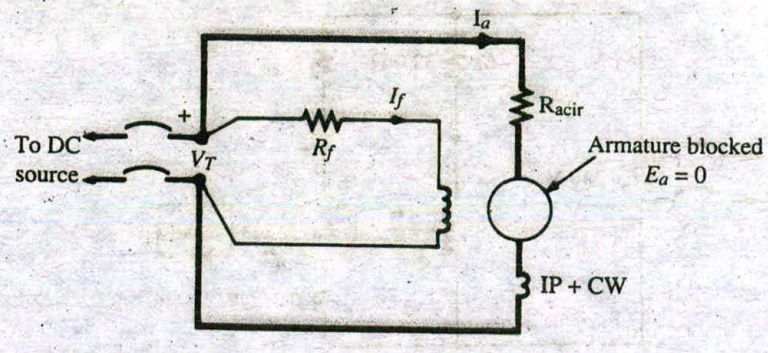


FIGURE 10.30
Circuit diagram for shunt motor with rotor blocked.

direct-current motors must have external resistors connected in series with the armature. Excessive armature current will cause destructive arcing and burning at the commutator–brush interface and the sudden impact to the driven equipment by the associated very high starting torque may cause mechanical damage to the driven equipment.

Manual Starter

With the exception of fractional horsepower motors, a DC motor requires the addition of external starting resistance to limit the current in the armature circuit when starting. This starting resistance must be left in the circuit until the cemf builds up sufficiently to reduce the armature current to a safe value. The value of starting resistance is generally selected to limit the current from 150 to 250 percent of rated value, depending on the starting torque required.

The shunt field is always connected across full-line voltage when starting, so that less armature current is needed to develop the required torque.

Figure 10.31 illustrates a rheostat type of manual starter connected to a shunt motor.[13] The circuit is closed when the lever is moved to the first contact, at which position all of the rheostat resistance is in series with the armature. As the machine accelerates, the lever should be moved slowly to the run position. The lever should not be left too long in an intermediate position or the starter will be damaged by overheating; the resistors are designed for intermittent duty, and should not be used for speed control.

The holding coil serves to hold the rheostat lever in the *run* position after all the resistance is cut out. It is connected in series with the shunt field of the motor, so that a break in the field circuit would de-energize the coil and permit the spring to pull the lever to the *off* position. The spring also returns the lever to the *off* position if there is a voltage failure or if the lever is left in some intermediate position.

[13]Automatic starters and motor controllers are discussed in Chapter 13.

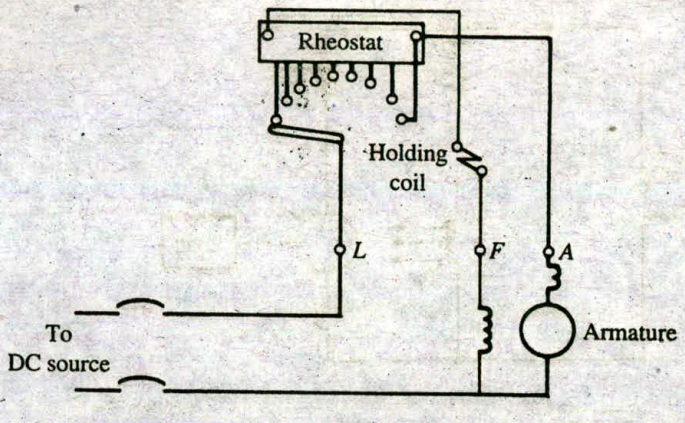


FIGURE 10.31
Connection diagram for a manually operated DC motor starter.

EXAMPLE 10.12 A 15-hp, 230-V, 1750 r/min shunt motor with a compensating winding draws 56.2 A when operating at rated conditions. The motor parameters are $R_{acir} = 0.280\ \Omega$ and $R_f = 137\ \Omega$. Determine (a) rated torque; (b) armature current at locked rotor if no starting resistance is used; (c) the external resistance required in the armature circuit that would limit the current and develop 200 percent rated torque when starting. (d) Assuming the system voltage drops to 215 V, determine the locked-rotor torque using the external resistor in (c).

Solution

(a) $$P = \frac{Tn}{5252} \quad \Rightarrow \quad T_{rated} = \frac{P \times 5252}{n} = \frac{15 \times 5252}{1750} = \underline{45.0\ \text{lb-ft}}$$

(b) The motor circuit is shown in Figure 10.32(a).

$$I_{a,lr} = \frac{V_T - E_a}{R_{acir}} = \frac{230 - 0}{0.280} = \underline{821.4\ \text{A}}$$

(c) The motor circuit with the starting resistor is shown in Figure 10.32(b).[14]

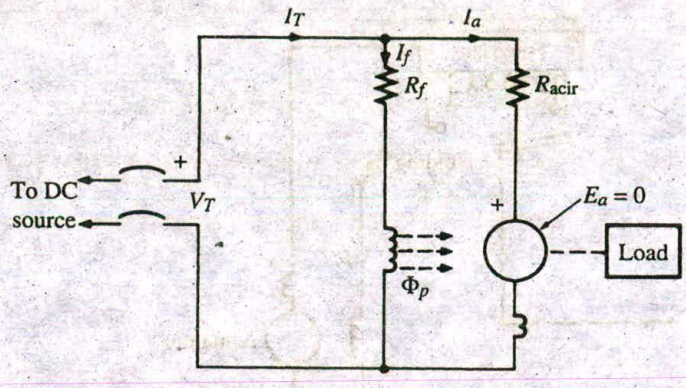
$$I_f = \frac{V_T}{R_f} = \frac{230}{137} = 1.68\ \text{A}$$

$$I_{a,rated} = I_{T,rated} - I_f = 56.2 - 1.68 = 54.52\ \text{A}$$

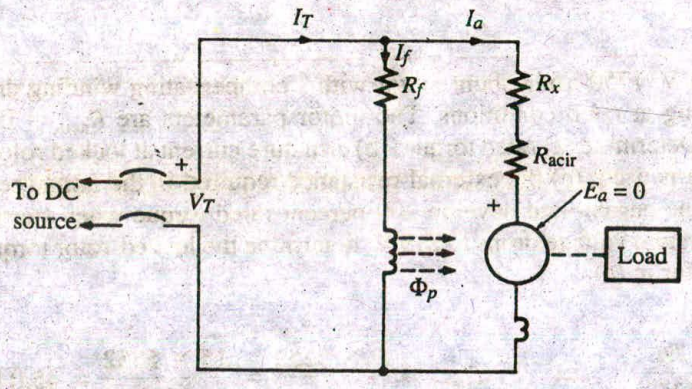
From Eq. (10–17), assuming constant flux density, the torque is proportional to the armature current. Hence, the armature current for 200 percent rated torque is

$$\frac{T_1}{T_2} = \frac{I_{a1}}{I_{a2}} \quad \Rightarrow \quad I_{a2} = I_{a1} \times \frac{T_2}{T_1} = 54.52 \times \frac{2T_1}{T_1} = \underline{109.0\ \text{A}}$$

[14]Practical motor controllers for large machines use two or more starting steps.



(a)



(b)

FIGURE 10.32
Circuits for Example 10.12: (a) without starting resistance; (b) with starting resistance.

Applying Kirchhoff's voltage law to the armature circuit with an external resistance in series with the armature, as shown in Figure 10.32(b),

$$V_T = E_a + I_a(R_{acir} + R_x) \quad \Rightarrow \quad R_x = \frac{V_T - E_a}{I_a} - R_{acir}$$

$$R_x = \frac{230 - 0}{109.0} - 0.280 = \underline{1.83\ \Omega}$$

(d) Since the magnetization curve for the specific machine is not available, it will be assumed that the flux density is proportional to the field current.

$$I_{f,215} = \frac{V_T}{R_f} = \frac{215}{137} = 1.57 \text{ A}$$

$$I_{a,215} = \frac{V_T - E_a}{R_{\text{acir}} + R_x} = \frac{215 - 0}{0.280 + 1.83} = 101.9 \text{ A}$$

Expressing Eq. (10–17) in terms of field current (reluctance assumed constant),

$$T_D \propto I_f I_a$$

Thus,

$$\frac{T_{D1}}{T_{D2}} = \frac{[I_f I_a]_1}{[I_f I_a]_2} \quad \Rightarrow \quad T_{D2} = T_{D1} \times \frac{[I_f I_a]_2}{[I_f I_a]_1}$$

Since the rotational losses such as windage and friction are not given, the rated torque will be taken as developed torque:

$$T_{D2} = 45.0 \times \frac{1.57 \times 101.9}{1.68 \times 54.52} = \underline{78.6 \text{ lb-ft}}$$

SUMMARY OF EQUATIONS FOR PROBLEM SOLVING

$$E_a = \frac{nPz_a\Phi_p}{60a} \quad \text{V} \qquad \textbf{(10–10)}$$

$$E_a = n\Phi_p k_G \quad \text{V} \qquad \textbf{(10–12)}$$

$$\Phi_p = \frac{N_f I_f}{\mathcal{R}} \quad \text{Wb} \qquad \textbf{(10–13)}$$

$$E_a = \frac{nN_f I_f k_G}{\mathcal{R}} \quad \text{V} \qquad \textbf{(10–14)}$$

$$I_f = \frac{E_{\text{bat}}}{R_f + R_{\text{rheo}}} \quad \text{A} \qquad \textbf{(10–15)}$$

$$\text{VR} = \frac{V_{\text{nl}} - V_{\text{rated}}}{V_{\text{rated}}} \times 100 \quad \text{percent} \qquad \textbf{(10–16)}$$

$$T_D = B_p I_a k_M \quad \text{lb-ft} \qquad \textbf{(10–17)}$$

$$\text{SR} = \frac{n_{\text{nl}} - n_{\text{rated}}}{n_{\text{rated}}} \times 100 \quad \text{percent} \qquad \textbf{(10–20)}$$

$$R_{\text{acir}} = R_a + R_{\text{IP}} + R_{\text{CW}} \quad \Omega \qquad \textbf{(10–24)}$$

$$n = \left.\frac{V_T - I_a R_{\text{acir}}}{\Phi_p k_G}\right|_{\Phi_p \neq 0} \tag{10–26}$$

$$P_{\text{mech}} = E_a I_a \quad \text{W} \tag{10–30}$$

$$P_{\text{mech}} = \frac{T_D n}{5252} \quad \text{hp} \tag{10–31}$$

$$T_D = \frac{7.04 E_a I_a}{n} \quad \text{lb-ft} \tag{10–33}$$

$$P_{\text{loss}} = P_{\text{acir}} + P_b + P_{\text{core}} + P_{\text{fcl}} + P_{f,w} + P_{\text{stray}} \quad \text{W} \tag{10–34}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{losses}}} \times 100 \tag{10–35}$$

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REVIEW QUESTIONS

1. What is the function of the commutator in (a) a DC generator; (b) a DC motor?
2. What is the neutral plane and where is it located?
3. Explain why the brushes of a DC machine must be located in the neutral plane.
4. What variables affect the torque developed in a DC machine?
5. What variables affect the voltage induced in a DC machine?
6. What apparatus is normally used to adjust the voltage of a shunt generator?
7. Is the induced emf in a motor or generator proportional to the field current? Explain.
8. Define voltage regulation.

9. Using appropriate sketches, explain in detail how torque is developed and voltage is generated in (a) motors; (b) generators.
10. What two methods can be used to reverse the direction of rotation of a shunt motor?
11. Using appropriate sketches, discuss the sequence of events that occur when loading a DC motor.
12. Using appropriate sketches, discuss the sequence of events that occur when removing load from a DC motor.
13. Define speed regulation.
14. How does the inductance of the armature affect the commutation process? Explain with the aid of sketches.
15. What are interpoles? Where are they located? How many are needed? What function do they serve?
16. What effect does saturation of the interpole iron have on the performance of DC generators when operating above rated load?
17. What effect does saturation of the interpole iron have on the performance of DC motors when operating above rated load?
18. Explain the effect of armature reaction on the performance of (a) DC generators; (b) DC motors.
19. What are compensating windings and what function do they serve? Explain how they work and why they are connected in series with the armature.
20. Do compensating windings eliminate the need for interpoles? Explain.
21. Under what conditions would it be necessary to shift the brush position of a modern DC motor? Explain.
22. (a) Sketch the complete equivalent circuit for a shunt generator and for a shunt motor, and label all parts. (b) Write Kirchhoff's voltage equation for the armature circuits in (a).
23. What is meant by the base speed of a DC motor?
24. Explain why inserting a resistor in series with the shunt field of a DC motor can cause an increase in speed.
25. Explain why a reduction in field flux will not always increase the speed of a DC motor.
26. Explain why inserting a resistor in series with the armature of a DC motor causes a decrease in speed.
27. Using appropriate sketches discuss the sequence of events that occurs when a resistor is placed in series with the armature of a running motor.
28. Using appropriate sketches discuss the sequence of events that occurs when a resistor is placed in series with the shunt field of a running motor.
29. What variables determine the torque at locked rotor?
30. Sketch the power-flow diagrams for a DC motor and for a DC generator. Label all losses.
31. What is brush-contact drop? What effect does it have on machine operation?
32. How may the efficiency of a DC motor be determined?
33. Explain why a resistor is needed in series with the armature when starting a DC motor, but is not needed when the motor is operating at its steady-state speed.

PROBLEMS

10–1/2 A 200-kW, eight-pole DC generator operating at 850 r/min has a generated emf of 200 V. Determine (a) the frequency of the induced emf; (b) the voltage and frequency if the speed is increased by 20 percent and the flux is decreased by 5 percent.

10–2/2 A 50-kW, 3500 r/min, 120-V, two-pole DC generator is operating at rated speed, rated air-gap flux, and no load. Determine the voltage and frequency of the generated voltage if the speed is increased by 15 percent and the flux is decreased by 6.2 percent.

10–3/7 The resistance of the shunt field winding and the resistance setting of the shunt field rheostat of a separately excited generator are 10.26 Ω and 14.23 Ω, respectively. The field circuit is connected to a 120-V DC source, and the magnetization curve for the machine is as shown in Figure 10.33. Sketch the equivalent circuit and determine (a) the induced emf; (b) the induced emf if a short in the rheostat caused the rheostat resistance to drop to 4.2 Ω.

10–4/7 A certain separately excited shunt generator has a shunt field winding resistance of 20.17 Ω and an armature resistance of 0.0014 Ω. The field winding is connected in series with a 40-Ω rheostat and supplied from a 240-V DC source. Assuming the magnetization curve for the machine is identical to that shown in Figure 10.33, determine (a) the induced emf if the rheostat is set to 0.0 Ω; (b) the setting of the rheostat (in ohms) required to reduce the generated voltage to 225 V.

10–5/8 A separately excited shunt generator rated at 1000 kW, 514 r/min, and 700 V has a no-load voltage of 725 V. Determine the voltage regulation.

10–6/8 A 100-kW, 1800 r/min shunt generator operating at rated load has a terminal voltage of 240 V. If the voltage regulation is 2.3 percent, determine the no-load voltage.

10–7/12 A 5-hp, 240-V, 1150 r/min shunt motor is operating at rated conditions. Determine the percent reduction in shunt field flux required to raise the speed to 1800 r/min. Assume the load on the shaft is adjusted to maintain rated armature current.

10–8/12 A 50-hp, 240-V, 650 r/min shunt motor operating at rated conditions draws a line current of 173 A. The motor has an armature resistance of 0.0705 Ω and a shunt field resistance of 81.63 Ω. If a reduction in load causes the armature current to drop to 70 percent of its rated value, determine (a) cemf; (b) speed; (c) line current.

10–9/12 A 5-hp, 120-V, 2500 r/min shunt motor draws 40 A when operating at rated conditions. Determine the new speed if the pole flux is reduced to 85 percent of its rated value and the load is adjusted so that the armature current is 28.6 A. $R_f = 63.8\ \Omega$ and $R_a = 0.252\ \Omega$.

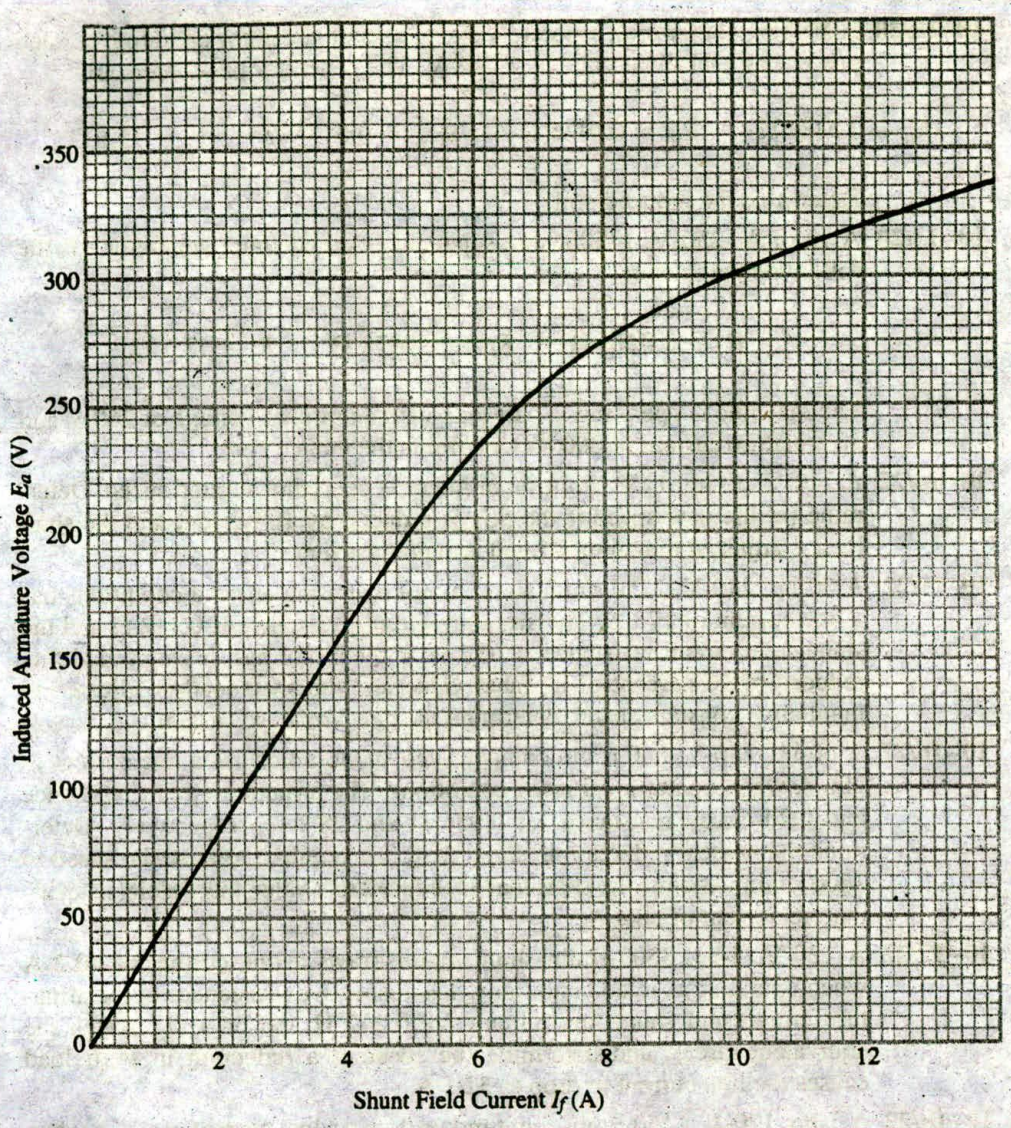


FIGURE 10.33
Magnetization curve for Problems 10–3/7 and 10–4/7.

10–10/12 A 15-hp, 240-V, 1150 r/min shunt motor draws 55 A when operating at rated conditions. The resistance of the shunt field windings is 109.1 Ω and the resistance of the armature is 0.364 Ω. Determine the no-load speed, assuming the total loss at no load is 970.6 W.

10–11/14 A 100-hp, 550-V, DC motor rated at 400 r/min has a speed regulation of 2.6 percent. Determine the speed if the load is removed.

10–12/20 A 50-kW, 1800 r/min, separately excited shunt generator operating at rated power has a terminal voltage of 248 V. The generator parameters are

$$R_a = 0.0487\ \Omega \qquad R_{IP} = 0.0111\ \Omega \qquad R_{CW} = 0.0125\ \Omega \qquad R_f = 75.6\ \Omega$$

Determine the induced emf.

10–13/20 A 125-kW, 250-V, 1450 r/min, separately excited shunt generator has the following parameters:

$$R_a = 0.0278\ \Omega \qquad R_{IP} = 0.0078\ \Omega \qquad R_f = 48.6\ \Omega$$

The machine is operating at part load with a terminal voltage of 260 V and an armature current of 300 A. Determine the induced emf.

10–14/22 A 240-V, 50-hp, 1150 r/min shunt motor is operating at rated speed. Determine (a) the new speed if the flux is reduced by 10 percent and the shaft load is adjusted to maintain rated armature current.

10–15/22 A 50-hp, 240-V, 1750 r/min shunt motor operating at rated conditions has a line current of 173 A. The armature-circuit resistance is 0.112 Ω and the shunt-field-circuit resistance is 70.2 Ω. If the motor has its shunt field flux reduced to 96 percent of its rated value and the shaft load is adjusted to maintain a constant speed, determine the new armature current.

10–16/22 A 60-hp, 240-V, 650 r/min compensated shunt motor has a line current of 206 A when operating at rated conditions. The armature-circuit resistance and field-circuit resistance are 0.084 Ω and 38.2 Ω, respectively. Determine the percent reduction in shunt field flux required to raise the speed to 1600 r/min. Assume the shaft load is reduced to a value that results in an armature current of 58.4 A.

10–17/22 A 120-V, 5-hp, 3500 r/min shunt motor draws a line current of 40.2 A when operating at rated conditions. The respective resistances of the armature circuit and shunt field circuit are 0.247 Ω and 66.4 Ω. Sketch the equivalent circuit and determine the speed if a reduction in shaft load causes the line current to drop to 32.1 A.

10–18/22 A 1-hp, 120-V, 1150 r/min shunt motor draws a line current of 9.5 A when operating at rated conditions. The respective resistances of the armature circuit and the shunt field circuit are 1.06 Ω and 252.6 Ω. Determine the resistance that must be connected in series with the armature to reduce the speed to 746 r/min, while developing the same torque.

10–19/22 A 240-V, 125-hp, 1150 r/min shunt motor operating at rated conditions, driving a constant-torque load, has a line current of 425 A. The armature-circuit resistance and field-circuit resistance are 0.0343 Ω and 47.1 Ω, respectively. Determine (a) the steady-state armature current if a 0.52-Ω resistor is connected in series with the armature, and a resistor inserted in

series with the shunt field causes a 10 percent reduction in field flux; (b) the steady-state speed for the conditions in (a).

10–20/25 A DC shunt motor with a compensating winding draws 72.4 A from a 500-V bus when delivering 40 hp at 1740 r/min. The motor parameters are $R_a = 0.465\ \Omega$, $R_{IP} = 0.134\ \Omega$, $R_{CW} = 0.026\ \Omega$, and $R_f = 208.3\ \Omega$. Determine (a) cemf; (b) mechanical power developed; (c) developed torque; (d) shaft torque.

10–21/25 A 15-hp, 3500 r/min, 240-V shunt motor draws 54.4 A when operating at rated conditions. The machine parameters are $R_a = 0.112\ \Omega$, $R_{IP} = 0.036\ \Omega$, and $R_f = 177.2\ \Omega$. Determine (a) cemf; (b) mechanical power developed; (c) developed torque; (d) shaft torque.

10–22/25 A 30-hp, 1150 r/min, six-pole shunt motor has an efficiency of 88.5 percent when operating at rated load from a 240-V supply. The motor parameters are $R_a = 0.064\ \Omega$, $R_f = 93.6\ \Omega$, and $R_{IP} = 0.0323\ \Omega$. Determine (a) mechanical power developed; (b) developed torque; (c) shaft torque.

10–23/25 A 20-hp, 240-V, four-pole shunt motor operating at one-half rated load runs at 3042 r/min and has an efficiency of 86.0 percent. The motor parameters are $R_a = 0.0731\ \Omega$, $R_{IP} = 0.033\ \Omega$, and $R_f = 123\ \Omega$. Determine (a) input power to motor; (b) mechanical power developed; (c) shaft torque.

10–24/26 A 60-hp, 240-V, 600 r/min shunt motor draws 152 A when operating at 75 percent shaft power. The armature-circuit resistance and field resistance are 0.0482 Ω and 41.2 Ω, respectively. The brushes are of electrographitic construction. Determine (a) electrical losses; (b) rotational losses; (c) efficiency.

10–25/26 A 150-kW, 250-V, 1750 r/min shunt generator is separately excited from a 240-V DC supply. The generator is operating at rated voltage and 50 percent load. The armature circuit has a resistance of 0.00728 Ω and the shunt field has a resistance of 64.0 Ω. The machine uses metal–graphite brushes and has a shaft power input of 106 hp. Determine (a) electrical losses; (b) rotational losses; (c) efficiency.

10–26/27 A 300-hp, 500-V, 1750 r/min shunt motor, operating at rated conditions, has an efficiency of 92.0 percent. The motor parameters are $R_{acir} = 0.042\ \Omega$, $R_f = 86.2\ \Omega$. Determine (a) rated shaft torque; (b) mechanical power developed; (c) developed torque at rated load; (d) external resistance required in series with the armature circuit to limit the locked-rotor current to 225 percent rated armature current; (e) developed torque for the conditions in (d).

10–27/27 A 30-hp, 240-V, 1150 r/min shunt motor operating at rated conditions has an efficiency of 88.5 percent. The motor parameters are $R_a = 0.064\ \Omega$, $R_{IP} = 0.0323\ \Omega$, and $R_f = 93.6\ \Omega$. Determine (a) rated shaft torque; (b) mechanical power developed; (c) developed torque at rated load; (d) external

resistance required in series with the armature circuit to limit the locked-rotor current to 175 percent rated armature current; (e) developed torque for the conditions in (d).

10–28/27 A 60-hp, 240-V, 850 r/min shunt motor has the following parameters: $R_a = 0.030\ \Omega$, $R_{IP} = 0.011\ \Omega$, and $R_f = 62.0\ \Omega$. The total losses when operating at rated conditions are 4.16 kW. Determine the external resistance required in series with the armature to limit the locked-rotor torque to 200 percent rated torque, if operating from a 220-V supply.

11

Direct-Current Motor Characteristics and Applications

11.1 INTRODUCTION

This chapter stresses the unique characteristics of shunt, series, and compound motors, and shows how the series field is used to shape the torque and speed characteristics of DC machines to meet the requirements of specific loads. Realistic calculations of motor speed using magnetization curves to account for magnetic saturation are compared with calculations using linear approximations. The adjustable-voltage method of speed control is introduced, along with applications for drive systems that require rapid reversing and speed adjustment over a wide range.

11.2 STRAIGHT SHUNT MOTORS

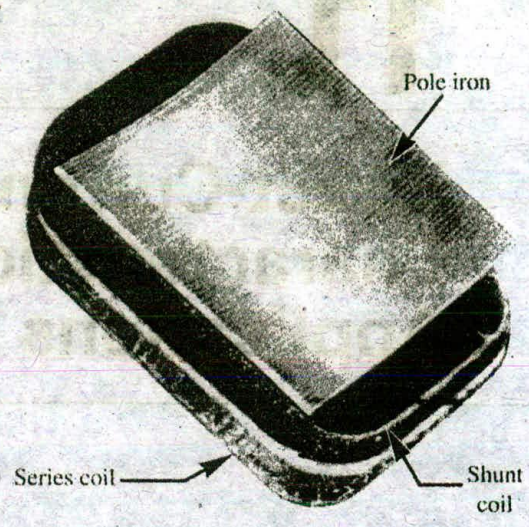
Straight shunt motors, previously discussed in Chapter 10, are essentially constant-speed machines. Slight weakening of the field due to armature-reaction effects, however, may cause a slight rise in speed with increasing load. Their principal fields of application include centrifugal pumps, fans, and other low starting-torque loads.

11.3 COMPOUND MOTORS

A compound motor has an additional winding, called a *series field* winding, wound with heavy copper conductor on top of the shunt field winding, as shown in Figure 11.1. The series field winding is connected in series with the armature as shown in Figure 11.2, so that its mmf will be proportional to the armature current, and in the *same direction* as the shunt field mmf.[1]

[1] Unless otherwise specified, compound motors are always assumed to be cumulative compound, that is, their shunt and series fields are additive.

FIGURE 11.1
Pole iron with shunt and series coils. (Courtesy TECO Westinghouse)



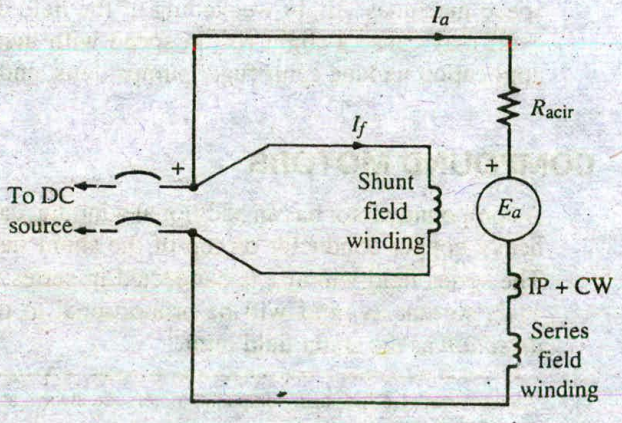
Typical compound motors designed for industrial applications obtain approximately 50 percent of their mmf from the series field when operating at rated load.

Stabilized-Shunt Motor

Compound motors, whose series fields are designed to provide just enough mmf to nullify the equivalent demagnetizing mmf of armature reaction and provide a very slight speed droop, are called stabilized-shunt motors.[2] The series field windings of such machines generally have one-half to one and a half turns/pole, and depending on

[2] The series field does not eliminate armature reaction. Elimination of armature reaction requires a compensating winding. See Sections 10.17 and 10.19 of Chapter 10.

FIGURE 11.2
Circuit diagram for a compound motor.



the application, provide approximately 3 to 10 percent of the total field mmf at rated load. The speed of stabilized-shunt motors is fairly constant, with only a slight droop in speed with increasing load. Stabilized-shunt motors are used in applications that require a fairly constant speed and a moderate starting torque.

11.4 BEWARE THE DIFFERENTIAL CONNECTION

Connections to the series and shunt windings must be such as to cause their respective mmfs to be additive.[3] If the series field is accidentally reversed with respect to the shunt field (differential connection), its mmf will subtract from the shunt field mmf, causing the net flux to decrease with increasing load, resulting in excessive speed. Furthermore, because of the difference in inductive time constants, the series field current builds up faster than the shunt field current. Hence, the motor will start in the wrong direction, and then, depending on the load and the number of series field turns/pole, may (1) slow down and stop, causing the overcurrent device to trip the machine from the bus; (2) slow down, stop, reverse direction, and accelerate to dangerously high speeds; or (3) slow down, stop, reverse, slow down, stop, reverse, etc., cycling continuously until tripped off the bus.

11.5 REVERSING THE DIRECTION OF ROTATION OF COMPOUND MOTORS

Reversing the direction of rotation of compound or stabilized-shunt motors is accomplished by reversing the armature branch as shown in Figure 11.3, or reversing both the series field and the shunt field. Reversing only the series field or only the shunt

[3] See Section 11.12 to determine the correct connections for shunt and series windings.

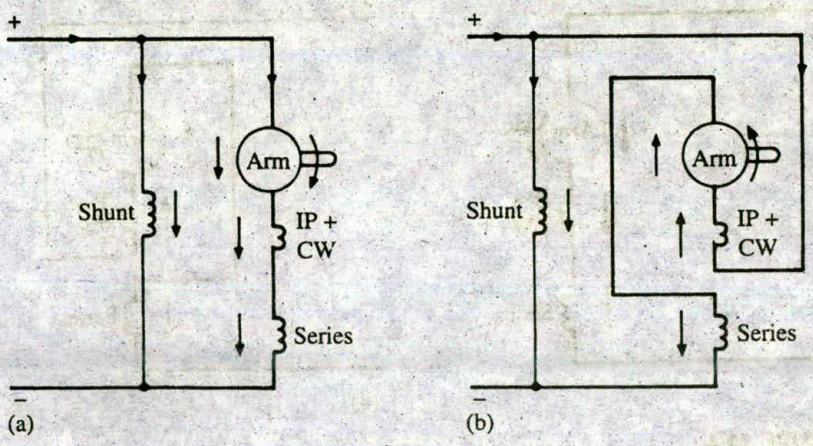


FIGURE 11.3
Reversing the direction of rotation of a compound motor by reversing the current in the armature, interpoles, and compensating winding.

field will result in a differential connection. The armature, interpoles, and compensating windings are treated as a single branch, and must be reversed as a unit. Reversing the armature without reversing the interpoles and compensating winding will cause severe arcing at the commutator–brush interface.

11.6 SERIES MOTOR

A series motor,[4] whose circuit is shown in Figure 11.4(a), is designed with a heavy series field, but has no shunt field to provide a base flux. With no shunt field to provide a base flux, a series motor will accelerate to damaging speeds if the shaft load is removed. Removing the load from a series motor causes $T_D > T_{load}$, resulting in an increase in motor speed. As the cemf starts to increase, it causes the armature current to decrease, which in turn causes the series field flux to decrease. The simultaneous opposing actions of increasing speed and decreasing flux, however, prevent the cemf from rising proportionately with speed. Thus, *I_a will decrease slowly with increasing speed.* Because the developed torque is proportional to $B_p I_a$, and because the armature current, and hence the flux density, do not decrease rapidly, loss of load will cause prolonged acceleration, resulting in destruction by centrifugal force.

Series motors must be connected directly to the load by solid couplings or gears, and the minimum load must be sufficient to limit the speed to a safe value. No belt drives are permitted.

Reversing the direction of rotation of a series motor is accomplished by reversing the current in the armature–interpole–compensating branch as shown in Figure 11.4(b), or reversing the current in the series field windings.

[4] See also universal motor in Section 7.9 of Chapter 7.

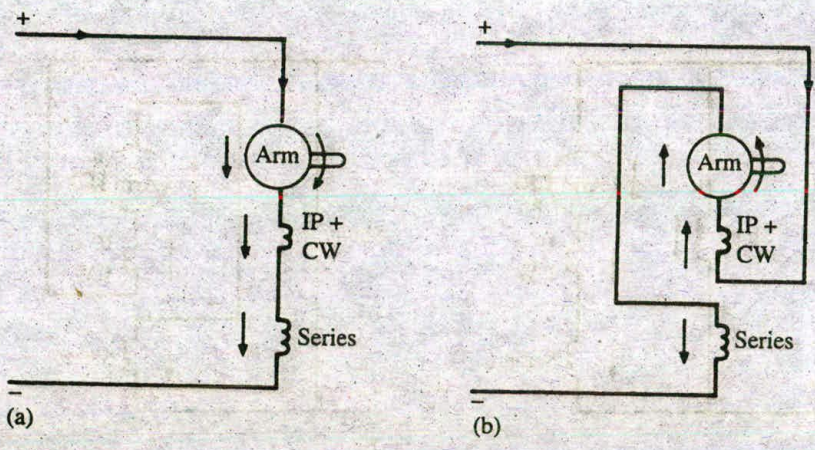


FIGURE 11.4
Reversing the direction of rotation of a series motor by reversing the current in the armature, interpoles, and compensating winding.

11.7 EFFECT OF MAGNETIC SATURATION ON DC MOTOR PERFORMANCE

Due to the effects of magnetic saturation, the pole flux is not directly proportional to the applied mmf. Hence, an accurate calculation of motor torque and motor speed for various operating conditions requires the use of a magnetization curve, such as that shown in Figure 11.5. Magnetization curves for specific machines are available from the manufacturer.

The net mmf that determines the pole flux includes components from the shunt field winding, series field winding, and armature reaction as applicable. For the general case, with all mmfs acting along the pole axis,

$$\mathcal{F}_{net} = \mathcal{F}_f + \mathcal{F}_s - \mathcal{F}_d \qquad \textbf{(11–1)}$$

where: $\mathcal{F}_{net}$ = net mmf (A-t/pole)
$\mathcal{F}_f$ = shunt field mmf ($N_f I_f$) (A-t/pole)
$\mathcal{F}_s$ = series field mmf ($N_s I_a$) (A-t/pole)
$\mathcal{F}_d$ = equivalent demagnetizing mmf due to armature reaction (A-t/pole)

Note: Although not exact, $\mathcal{F}_d$ is assumed proportional to the armature current. If a compensating winding is used, however, $\mathcal{F}_d = 0$.

As previously shown in Chapter 10, the developed torque and speed of a DC motor can be determined from

$$T_D = B_p I_a k_M \qquad \textbf{(10–17)}$$

$$n = \left.\frac{V_T - I_a R_{acir}}{\Phi_p k_G}\right|_{\Phi_p \neq 0} \qquad \textbf{(10–26)}$$

$$R_{acir} = R_a + R_{IP} + R_{CW} + R_s$$

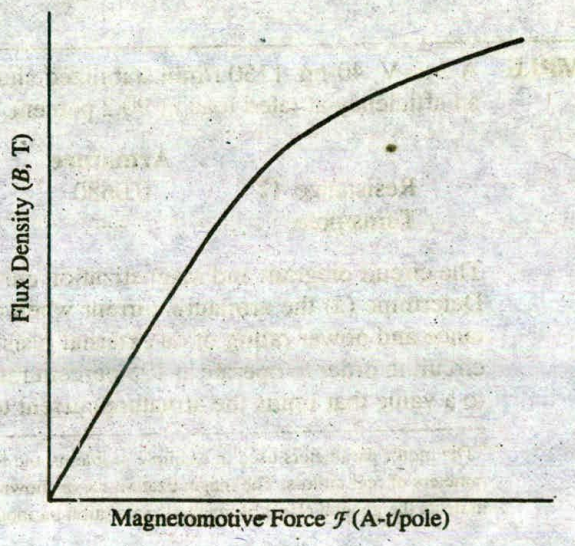


FIGURE 11.5
Typical magnetization curve for a DC motor.

where: R_{acir} = resistance of armature circuit (Ω)
R_a = resistance of armature windings (Ω)
R_{IP} = resistance of interpole windings (Ω)
R_{CW} = resistance of compensating windings (Ω)
R_s = resistance of series field winding (Ω)
B_p = air-gap flux density (T)
Φ_p = pole flux (Wb)

Constants k_G and k_M depend on the design of the machine, type of armature winding, and units used.

When solving problems to determine the effect of different values of pole flux and armature current on the developed torque and speed of the machine, it is convenient to use the following ratios based on Eqs. (10–17) and (10–26), respectively. Flux fringing is assumed to be negligible.

$$\frac{T_{D1}}{T_{D2}} = \frac{[B_p I_a]_1}{[B_p I_a]_2} \tag{11–2}$$

$$\frac{n_1}{n_2} = \frac{\left[\dfrac{V_T - I_a R_{acir}}{\phi_p k_G}\right]_1}{\left[\dfrac{V_T - I_a R_{acir}}{\phi_p k_G}\right]_2}, \qquad \phi \neq 0 \tag{11–3}$$

Subscripts 1 and 2 denote different sets of conditions.

Substituting $\phi_p = B_p \times A$ in Eq. (11–3), where A is the cross-sectional area of a pole, and simplifying,

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{acir}}{B_p}\right]_1 \times \left[\frac{B_p}{V_T - I_a R_{acir}}\right]_2 \tag{11–4}$$

EXAMPLE 11.1 A 240-V, 40-hp, 1150 r/min stabilized-shunt motor, operating at rated conditions, has an efficiency at rated load of 90.2 percent. The motor parameters are:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.0680	0.0198	0.00911	99.5
Turns/pole	—	—	$\frac{1}{2}$	1231

The circuit diagram and magnetization curve[5] for the motor are shown in Figure 11.6. Determine (a) the armature current when operating at rated conditions; (b) the resistance and power rating of an external resistance required in series with the shunt field circuit in order to operate at 125 percent rated speed. Assume the shaft load is adjusted to a value that limits the armature current to 115 percent of rated current.

[5] The motor parameters used in example problems and homework problems are, or closely approximate, the parameters of real motors. The magnetization curve shown in Figure 11.6 is hypothetical, but reasonable, and does indicate the general effect of magnetic saturation on motor performance.

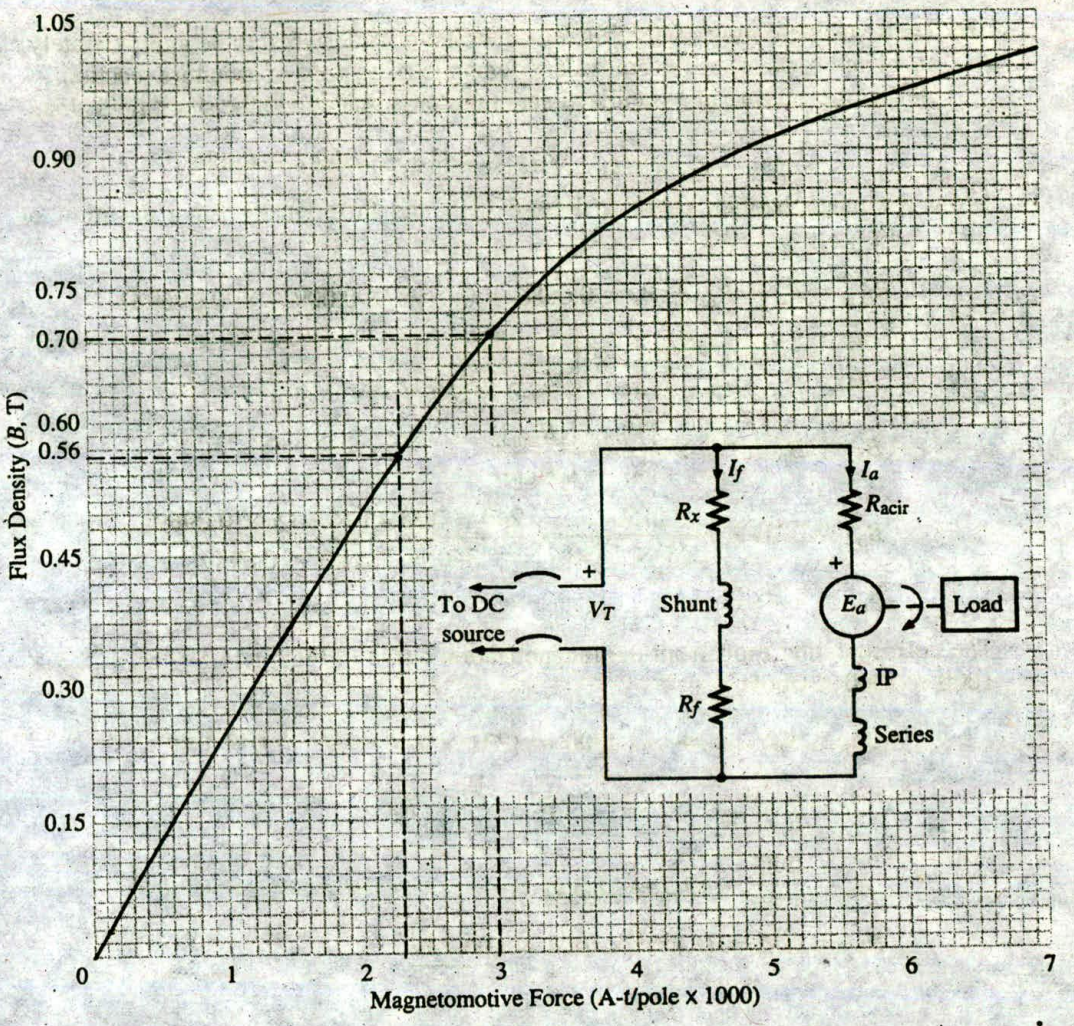


FIGURE 11.6
Magnetization curve and circuit diagram for Example 11.1.

Solution

(a) $P = V_T I_T \quad \Rightarrow \quad \dfrac{40 \times 746}{0.902} = 240 \times I_T \quad \Rightarrow \quad I_T = 137.84 \text{ A}$

$$I_f = \frac{V_T}{R_f} = \frac{240}{99.5} = 2.4121 \text{ A}$$

$$I_a = I_T - I_f = 137.84 - 2.41 = \underline{135.43 \text{ A}}$$

(b) The series field mmf of a stabilized-shunt motor is designed to be approximately equal and opposite to the equivalent demagnetizing mmf of armature reaction. Hence, the net flux in a stabilized-shunt motor is that due to the shunt field alone.

$$\mathcal{F}_{net} = \mathcal{F}_f = N_f I_f = 1231 \times 2.412 = 2969.2 \text{ A-t/pole}$$

From the magnetization curve in Figure 11.6, the flux density for a net mmf of 2969 A-t/pole is ≈0.70 T.

$$R_{acir} = R_a + R_{IP} + R_s = 0.0680 + 0.0198 + 0.00911 = 0.0969\ \Omega$$

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{acir}}{B_p}\right]_1 \times \left[\frac{B_p}{V_T - I_a R_{acir}}\right]_2$$

$$B_{p2} = B_{p1} \times \frac{n_1}{n_2} \times \frac{[V_T - I_a R_{acir}]_2}{[V_T - I_a R_{acir}]_1}$$

$$B_{p2} = 0.70 \times \frac{1150}{1.25 \times 1150} \times \frac{240 - 135.43 \times 1.15 \times 0.0969}{240 - 135.43 \times 0.0969}$$

$$B_{p2} = 0.56 \text{ T}$$

The corresponding mmf from the magnetization curve in Figure 11.6 is $\mathcal{F}_f \approx 2.3 \times 1000 = 2300$ A-t/pole.

$$\mathcal{F}_f = N_f I_f \quad \Rightarrow \quad 2300 = 1231 \times I_f \quad \Rightarrow \quad I_f = 1.87 \text{ A}$$

$$I_f = \frac{V_T}{R_f + R_x} \quad \Rightarrow \quad R_x = \frac{V_T}{I_f} - R_f$$

$$R_x = \frac{240}{1.87} - 99.5 \approx \underline{28.8\ \Omega}$$

$$P_{R_x} = I_f^2 R_x = (1.87)^2 \times 28.8 \approx \underline{100.7 \text{ W}}$$

EXAMPLE 11.2 An 850 r/min, 125-hp, 240-V compound motor has the following parameters:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.0172	0.005	0.0023	49.2
Turns/pole	—	—	4.5	577

The circuit diagram and magnetization curve are shown in Figure 11.7. Approximately 10 percent of the series field mmf is used to offset the demagnetizing action of armature reaction. The efficiency at rated load is 85.4 percent, and the machine is driving a constant-torque load. Determine (a) shunt field current; (b) armature current; (c) developed torque; (d) the armature current if a resistor inserted in series with the shunt field caused the speed to increase to 900 r/min; (e) the external resistance required in series with the shunt field in order to obtain 900 r/min.

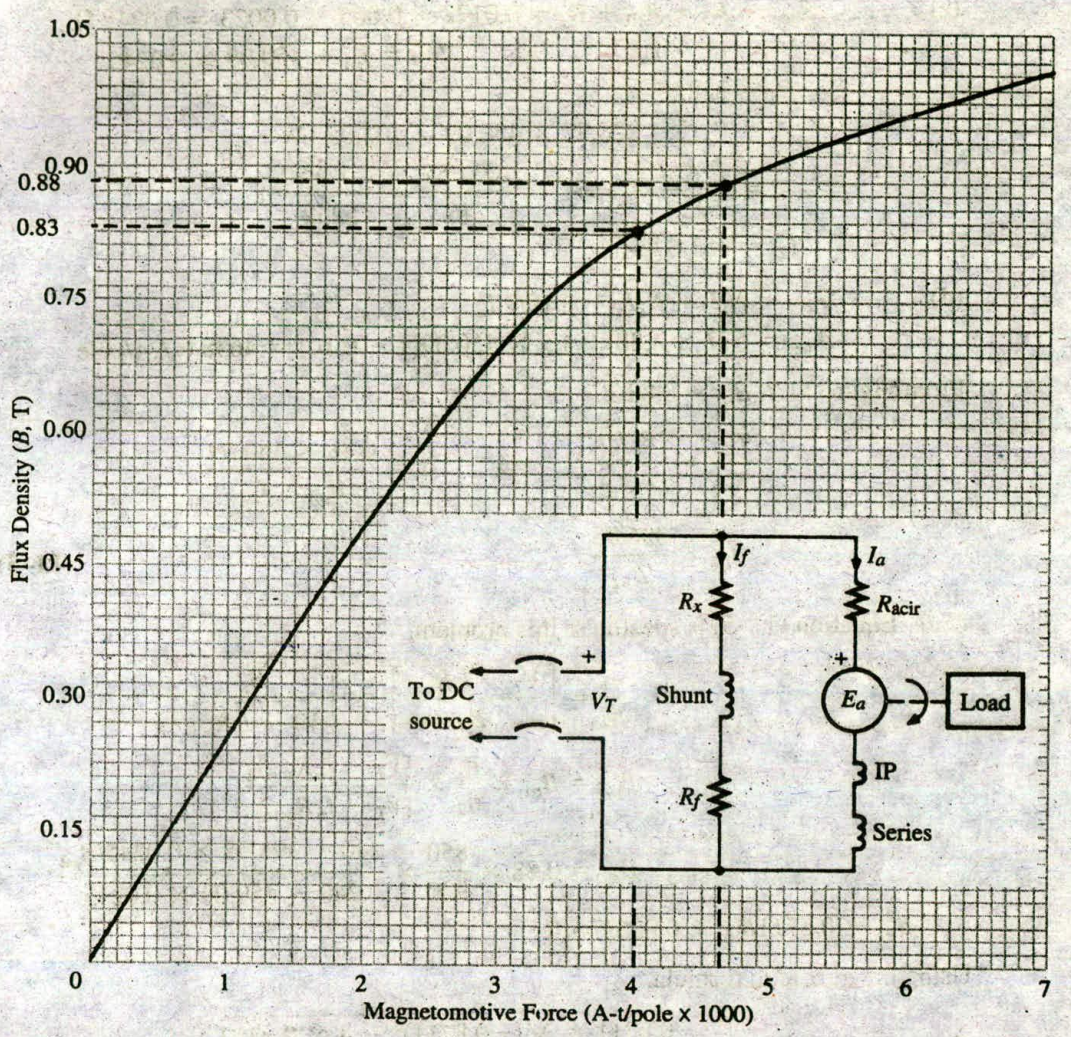


FIGURE 11.7
Magnetization curve and circuit diagram for Example 11.2.

Solution

(a)
$$I_f = \frac{V_T}{R_f} = \frac{240}{49.2} = \underline{4.88 \text{ A}}$$

(b)
$$P_{\text{in}} = \frac{P_{\text{out}}}{\eta} \quad \Rightarrow \quad 240 \times I_T = \frac{125 \times 746}{0.854} \quad \Rightarrow \quad I_T = 454.97 \text{ A}$$

$$I_a = I_T - I_f = 454.97 - 4.88 = \underline{450.09 \text{ A}}$$

(c)

$$R_{acir} = R_a + R_{IP} + R_s = 0.0172 + 0.005 + 0.0023 = 0.0245\ \Omega$$

$$V_T = E_a + I_a R_{acir} \quad \Rightarrow \quad 240 = E_a + 450.09 \times 0.0245$$

$$E_a = 228.97\ \text{V}$$

$$P_{mech} = E_a I_a = 228.97 \times 450.09 = 103{,}057\ \text{W}$$

$$P = \frac{T \times n}{5252} \quad \Rightarrow \quad \frac{103{,}057}{746} = \frac{T \times 850}{5252}$$

$$T_D = \underline{853.6\ \text{lb-ft}}$$

(d)

$$\mathcal{F}_{net} = N_f I_f + N_s I_a - 0.10 N_s I_a$$

$$\mathcal{F}_{net} = 577 \times 4.88 + 4.5 \times 450.09(1 - 0.10) = 4638.6\ \text{A-t/pole}$$

From Figure 11.7, $B_{p1} \approx 0.88$ T.

$$\frac{T_{D1}}{T_{D2}} = \frac{[B_p I_a]_1}{[B_p I_a]_2} \quad \Rightarrow \quad 1 = \frac{0.88 \times 450.09}{B_{p2} \times I_{a2}}$$

$$I_{a2} = \frac{396.08}{B_{p2}} \tag{11–5}$$

Note: Equation (11–5) is specific to this problem.

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{acir}}{B_p}\right]_1 \times \left[\frac{B_p}{V_T - I_a R_{acir}}\right]_2$$

$$B_{p2} = B_{p1} \times \frac{n_1}{n_2} \times \frac{[V_T - I_a R_{acir}]_2}{[V_T - I_a R_{acir}]_1}$$

$$B_{p2} = 0.88 \times \frac{850}{900} \times \frac{240 - 396.08 \times 0.0245/B_{p2}}{240 - 450.09 \times 0.0245}$$

$$B_{p2}^2 - 0.8711 B_{p2} + 0.0352 = 0$$

Using the quadratic formula,

$$B_{p2} = \frac{0.8711 \pm \sqrt{(-0.8711)^2 - 4 \times 0.0352}}{2}$$

$$B_{p2} \approx 0.83\ \text{T}, \qquad 0.043\ \text{T}$$

Substituting into Eq. (11–5)

$$I_{a2} = \frac{396.08}{0.83} = 477\ \text{A} \qquad I_{a2} = \frac{396.08}{0.043} = 9211\ \text{A}$$

Speaking "mathematically," the motor will operate at 900 r/min with a flux density of ≈0.83 T, or ≈0.043 T. A flux density of 0.043 T, however, will cause a prohibitively high armature current of 9211 A that is essentially equivalent to a short circuit; the motor will be severely damaged, if not totally destroyed, if protective devices do not "instantaneously" trip the machine from the line.

Given a choice between two values of flux density for a given load condition, the higher value of flux density will result in a lower armature current, and is the mandatory selection.

The value of B_{p2} may be approximated by using a simpler approach which assumes that the *IR* drop in the armature circuit will be very small for all load conditions up to rated load. Based on this assumption, the cemf will be essentially constant ($E_a = V_T - I_a R_{acir}$). From Eq. (10–13), Chapter 10,

$$I_a = \frac{nT_D}{7.04E_a}$$

Thus, with T_D constant, and E_a essentially constant, $I_a \propto n$.

$$\frac{n_2}{n_1} \approx \frac{I_{a2}}{I_{a1}} \Rightarrow I_{a2} = I_{a1} \cdot \frac{n_2}{n_1} = 450.09 \times \frac{900}{850} = 477 \text{ A}$$

Substituting into Eq. (11–5),

$$B_{p2} = \frac{396.08}{477} = 0.83 \text{ T}$$

(e) From the magnetization curve in Figure 11.7, the mmf ($\mathcal{F}_2$) corresponding to 0.83 T is ≈4000 A-t/pole.

$$\mathcal{F}_2 = N_f I_{f2} + N_s I_{a2} - 0.10 \times N_s I_{a2}$$

$$I_{f2} = \frac{\mathcal{F}_2 - 0.90 \times N_s I_{a2}}{N_f}$$

$$I_{f2} = \frac{4000 - 0.90 \times 4.5 \times 477}{577} \approx 3.58 \text{ A}$$

$$I_{f2} = \frac{V_T}{R_f + R_x} \quad \Rightarrow \quad R_x = \frac{V_T}{I_{f2}} - R_f$$

$$R_x = \frac{240}{3.58} - 49.2 \approx \underline{17.8\ \Omega}$$

EXAMPLE 11.3 A 100-hp, 650 r/min, 240-V series motor has an efficiency of 89.6 percent when operating at rated conditions. The series field has 14 turns/pole, and the equivalent demagnetizing mmf due to armature reaction is approximately 8.0 percent of the series field mmf. The motor parameters are:

	Armature	Interpole	Series
Resistance, Ω	0.0202	0.00588	0.00272

The circuit diagram and magnetization curve for the motor are shown in Figure 11.8. Determine the speed if the load is reduced to a value that causes the armature current to be 30 percent rated current.

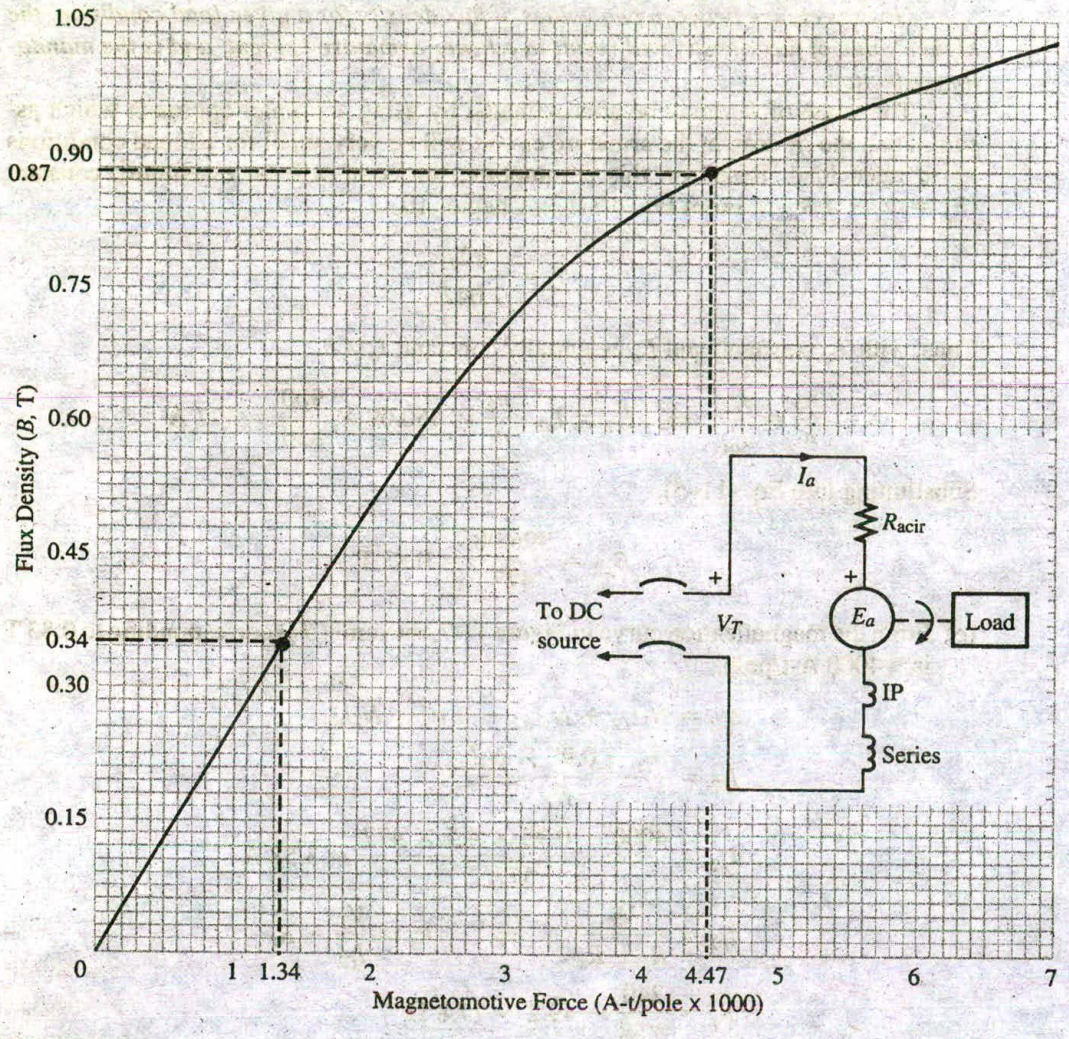


FIGURE 11.8
Magnetization curve and circuit diagram for Example 11.3.

Solution

$$P = V_T I_T = \frac{100 \times 746}{0.896} = 240 \times I_T \quad \Rightarrow \quad I_a = I_T = 346.91 \text{ A}$$

$$R_{acir} = 0.0202 + 0.00588 + 0.00272 = 0.0288\ \Omega$$

$$\mathcal{F}_{net1} = \mathcal{F}_s - \mathcal{F}_d = N_s I_a (1 - 0.080) = 14 \times 346.91 \times 0.92 = 4468.2 \text{ A-t/pole}$$

From the magnetization curve in Figure 11.8, $B_{p1} \approx 0.87$ T.

$$\mathcal{F}_{net2} = 0.30 \times \mathcal{F}_{net1} = 0.30 \times 4468.2 = 1340.5 \text{ A-t/pole}$$

From the magnetization curve, $B_{p2} \approx 0.34$ T.

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{\text{acir}}}{B_p}\right]_1 \times \left[\frac{B_p}{V_T - I_a R_{\text{acir}}}\right]_2$$

$$\frac{650}{n_2} = \left[\frac{240 - 346.91 \times 0.0288}{0.87}\right] \times \left[\frac{0.34}{240 - 0.30 \times 346.91 \times 0.0288}\right]$$

$$n_2 = \underline{1714 \text{ r/min}}$$

11.8 LINEAR APPROXIMATIONS

If the specific magnetization curve is not available for the solution of problems involving changes in the magnetic field, a *rough approximation* may be obtained by assuming saturation effects to be negligible. It should be understood, however, that the series field of heavily compounded motors can drive the magnetic field into deep saturation, especially under locked-rotor and high-overload conditions. Thus, speed and torque calculations involving locked rotor and high overloads of compound motors will be substantially in error if saturation effects are ignored.

If the conditions of a problem indicate that the net mmf is to be reduced below its rated value, an approximation using a linear assumption will provide information as to the approximate value of required rheostat resistance.

A linear approximation of the torque and speed equations is obtained by expressing the flux and flux density in terms of the net mmf. Thus, assuming, saturation effects are negligible, Eqs. (11–2) and (11–4) can be expressed as

$$\frac{T_{D1}}{T_{D2}} = \frac{[\mathcal{F}_{\text{net}} I_a]_1}{[\mathcal{F}_{\text{net}} I_a]_2} \tag{11–6}$$

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{\text{acir}}}{\mathcal{F}_{\text{net}}}\right]_1 \times \left[\frac{\mathcal{F}_{\text{net}}}{V_T - I_a R_{\text{acir}}}\right]_2, \qquad \phi \neq 0 \tag{11–7}$$

Series Motor

If the range of series-motor operation is in the unsaturated region, and armature reaction effects are negligible or compensated for, then Eq. (11–6) for the series motor becomes

$$\begin{aligned} T_{D,\text{series}} &\propto \mathcal{F}_{\text{net}} I_a = N_s I_a \cdot I_a \\ T_{D,\text{series}} &\propto I_a^2 \end{aligned} \tag{11–8}$$

As indicated in Eq. (11–8), for the conditions specified *the torque developed by a series motor is essentially proportional to the square of the armature current.*

EXAMPLE 11.4 Example 11.1 is re-solved using a linear approximation, and the solution is compared with the results obtained in Example 11.1.

Solution

Using the data and preliminary calculations in Example 11.1,

$$I_{f1} = \frac{V_T}{R_f} = \frac{240}{99.5} = 2.412 \text{ A}$$

$$I_{a1} = I_T - I_f = 137.84 - 2.412 = 135.43 \text{ A}$$

$$\mathcal{F}_{net} = \mathcal{F}_f = 1231 \times 2.412 = 2969.2 \text{ A-t/pole}$$

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{acir}}{\mathcal{F}_{net}}\right]_1 \times \left[\frac{\mathcal{F}_{net}}{V_T - I_a R_{acir}}\right]_2$$

$$\mathcal{F}_{net2} = \mathcal{F}_{net1} \times \frac{n_1}{n_2} \times \frac{[V_T - I_a R_{acir}]_2}{[V_T - I_a R_{acir}]_1}$$

$$\mathcal{F}_{net2} = 2969.2 \times \frac{1150}{1.25 \times 1150} \times \frac{240 - 135.43 \times 1.15 \times 0.0969}{240 - 135.43 \times 0.0969}$$

$$\mathcal{F}_{net2} = 2354.8 \text{ A-t/pole}$$

$$I_f = \frac{\mathcal{F}_{net}}{N_f} = \frac{2354.8}{1231} = 1.91 \text{ A}$$

$$I_f = \frac{V_T}{R_f + R_x} \quad \Rightarrow \quad R_x = \frac{V_T}{I_f} - R_f$$

$$R_x = \frac{240}{1.91} - 99.5 = \underline{26.15\ \Omega}$$

The rheostat resistance determined in Example 11.1 using the magnetization curve is 28.8 Ω. The error due to linear approximation is

$$\frac{28.8 - 26.15}{28.8} \times 100 \approx 9.2\%$$

The lower calculated value of rheostat resistance as determined through linear approximation would cause a slightly higher field current, and hence a slightly lower speed than the desired $1.25 \times 1150 = 1437.5$ r/min.

EXAMPLE 11.5 Example 11.2 is re-solved using a linear approximation to show the gross error that occurs when a linear assumption is applied to compound motors operating at overload conditions.

Solution

Using the data and preliminary calculations in Example 11.2,

$$\mathcal{F}_{net,1} = N_f I_f + N_s I_a - 0.10 \times N_s I_a$$

$$\mathcal{F}_{net,1} = 577 \times 4.88 + 4.5 \times 450.09 \times 0.90 = 4638.6 \text{ A-t/pole}$$

$$\frac{T_{D1}}{T_{D2}} = \frac{[\mathcal{F}_{net} I_a]_1}{[\mathcal{F}_{net} I_a]_2} \quad \Rightarrow \quad 1 = \frac{4638.6 \times 450.09}{\mathcal{F}_2 \times I_{a2}}$$

$$I_{a2} = \frac{2{,}087{,}787.5}{\mathcal{F}_2}$$

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{acir}}{\mathcal{F}_{net}}\right]_1 \times \left[\frac{\mathcal{F}_{net}}{V_T - I_a R_{acir}}\right]_2$$

$$\mathcal{F}_2 = \mathcal{F}_1 \times \frac{n_1}{n_2} \times \frac{[V_T - I_a R_{acir}]_2}{[V_T - I_a R_{acir}]_1}$$

$$\mathcal{F}_2 = 4638.6 \times \frac{850}{900} \times \frac{240 - 2{,}087{,}787.5 \times 0.0245/\mathcal{F}_2}{240 - 450.09 \times 0.0245}$$

$$\mathcal{F}_2^2 - 4591.9\mathcal{F}_2 + 978{,}660 = 0$$

Using the quadratic formula,

$$\mathcal{F}_2 = \frac{4591.9 \pm \sqrt{(-4591.9)^2 - 4 \times 978{,}660}}{2}$$

$$\mathcal{F}_2 = 4367.8 \text{ A-t/pole}, \qquad 224.1 \text{ A-t/pole}$$

Taking the larger mmf, which results in a smaller armature current,

$$\mathcal{F}_{net,2} = \underline{4367.8 \text{ A-t/pole}}$$

$$I_{a2} = \frac{2{,}087{,}787.5}{\mathcal{F}_2} = \frac{2{,}087{,}787.5}{4367.8} = 478.0 \text{ A}$$

$$\mathcal{F}_{net,2} = N_f I_f + N_s I_a \times 0.90 \quad \Rightarrow \quad I_{f2} = \frac{\mathcal{F}_{net} - N_s I_a \times 0.90}{N_f}$$

$$I_{f2} = \frac{4367.8 - 4.5 \times 478.0 \times 0.90}{577} = 4.21 \text{ A}$$

$$I_{f2} = \frac{V_T}{R_f + R_x} \quad \Rightarrow \quad R_x = \frac{V_T}{I_{f2}} - R_f$$

$$R_x = \frac{240}{4.21} - 49.2 = \underline{7.74\ \Omega}$$

The rheostat resistance determined in Example 11.2 using the magnetization curve is 17.8 Ω. The error introduced by linear approximation is

$$\frac{17.8 - 7.74}{17.8} \times 100 \approx 56.5\%$$

11.9 COMPARISON OF STEADY-STATE OPERATING CHARACTERISTICS OF DC MOTORS

The steady-state operating characteristics of typical shunt, compound, and series motors, of the same torque and speed ratings, operating from a *constant-voltage* DC supply, are shown in Figure 11.9.

Shunt Motor

As indicated by its operating characteristics, the speed of a shunt motor is relatively constant from no load to rated load and is attributed to the essentially constant flux provided by the shunt field. The speed regulation of the shunt motor is approximately 5 percent. The internal torque developed by a shunt motor is dependent on the flux

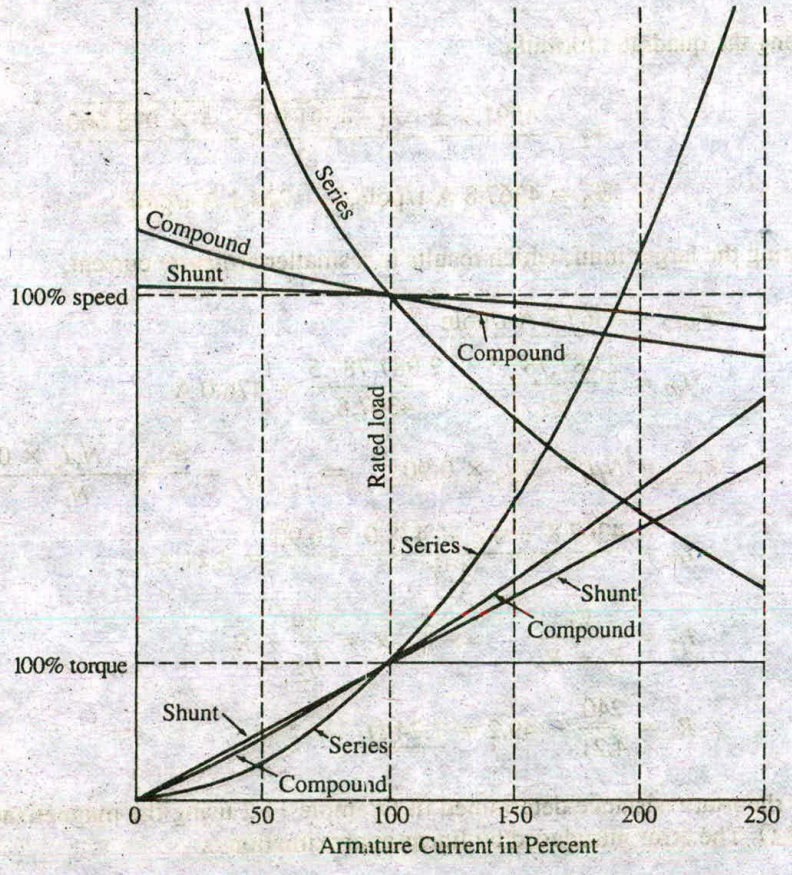


FIGURE 11.9
Steady-state speed and torque characteristics of typical shunt, series, and compound motors.

density and the armature current. Hence, the constant field of the shunt machine will cause the developed torque to vary almost linearly with the armature current. The shunt motor has its greatest field of application with loads that require essentially constant speed, and where high starting torques are not needed. Shunt motors are used to drive centrifugal pumps, fans, winding reels, conveyors, machine tools, and other loads of similar characteristics.

Compound Motor

The torque that a compound motor develops for values of armature current above the rated value is much higher than that of a shunt machine with the same rated power and base speed. The higher torque values of the compound machine, however, are accompanied by lower speeds. The speed regulation of compound motors is generally between 15 and 25 percent. The compound motor has its greatest application with loads that require high starting torques or have pulsating loads. They are used to drive electric shovels, metal-stamping machines, reciprocating pumps, hoists, compressors, and other loads of similar characteristics. Compound motors smooth out the energy demand required of a pulsating load. The motor slows down during the work stroke, giving up the energy stored in its moving parts, and at the same time developing a greater internal torque. During the recovery stroke, the motor accelerates and restores energy to the moving parts. Thus, the demand from the electrical system is less than if a shunt motor were used. A shunt motor would tend to maintain the same speed during the work stroke, causing excessive current demands from the electrical system.

Series Motor

The high ratio of light-load to full-load speed, coupled with its high starting torque, makes the series motor adaptable to driving hoists, electric locomotives, and other loads of similar characteristics. As indicated by its speed curve, completely removing the load from a series motor will cause it to "run away." Hence, series motors must be directly connected to the load by gears or a solid coupling and should not be applied to loads that can be removed or reduced sufficiently to cause overspeeding.

11.10 ADJUSTABLE-VOLTAGE DRIVE SYSTEMS

An adjustable-voltage drive system provides acceleration, deceleration, and speed control for *shunt* and *stabilized-shunt* motors by providing an adjustable voltage to the armature, while maintaining a constant voltage supply to the shunt field circuit.

An elementary circuit diagram of a simple adjustable-voltage drive system, called the *Ward–Leonard* system, is shown in Figure 11.10 for a small vessel. The prime mover driving the generator may be a diesel engine, turbine, or other machine that can provide an essentially constant speed. A small generator (not shown) supplies the excitation bus. The generator rheostat provides speed control from a creeping speed to the base speed of the motor, and also provides a means for reversing the rotation by reversing the polarity of the generator. The broken lines indicate the position

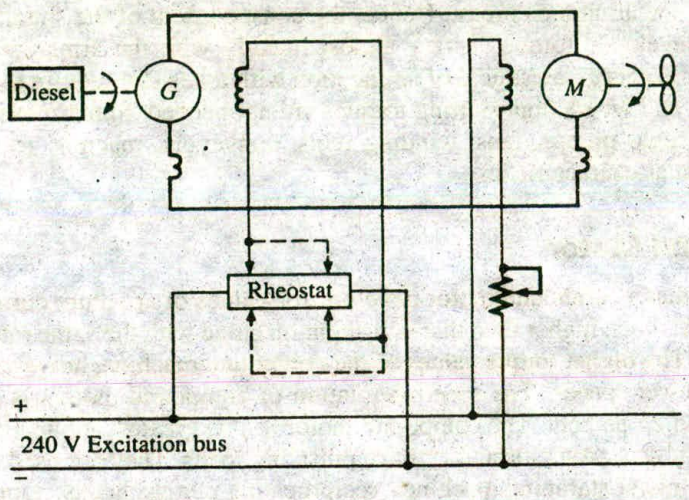


FIGURE 11.10
Elementary circuit diagram of a simple adjustable-voltage drive system.

of the sliding contacts for opposite rotation of the motor. The two sliding contacts are moved simultaneously in different directions by a single operating lever. The armature current is reduced to zero by centering the sliding contacts.

Although obsolete in terms of more modern methods of control, the Ward–Leonard system is still used in some of the older mine hoists, electric shovels, mills, etc. Drive systems for new plants and modernization of older plants use solid-state control.

EXAMPLE 11.6 The adjustable-voltage DC drive system shown in Figure 11.10 has an armature rated at 750 V, 1600 hp, 955 r/min. The armature current and field current at rated load are 1675 A and 5.20 A, respectively. The motor has a compensating winding, and the separately excited shunt field is fed through a rheostat from the 240-V excitation bus. The motor parameters are:

	Armature	IP + CW	Shunt
Resistance, Ω	0.00540	0.00420	14.70

The power required by the propeller load varies as the cube of the speed. Determine (a) torque developed when operating at rated speed; (b) developed torque required at half rated-speed; (c) armature voltage required for half rated-speed, assuming rated field current.

Solution

(a)
$$R_{\text{acir}} = R_a + R_{\text{IP+CW}} = 0.00540 + 0.00420 = 0.00960\ \Omega$$
$$V_T = E_a + I_a R_{\text{acir}} \quad \Rightarrow \quad 750 = E_a + 1675 \times 0.00960$$
$$E_a = 733.92\ \text{V}$$

$$P_{\text{mech}} = E_a I_a = 733.92 \times 1675 = 1{,}229{,}316 \text{ W}$$

$$P = \frac{T \times n}{5252} \quad \Rightarrow \quad \frac{1{,}229{,}316}{746} = \frac{T \times 955}{5252}$$

$$T_D = \underline{9062.5 \text{ lb-ft}}$$

(b)

$$P \propto n^3 \quad \Rightarrow \quad T \times n \propto n^3$$

$$\therefore T \propto n^2$$

$$\frac{T_1}{T_2} = \left(\frac{n_1}{n_2}\right)^2 \quad \Rightarrow \quad T_2 = T_1 \times \left(\frac{n_2}{n_1}\right)^2$$

$$T_2 = 9062.5 \times \left(\frac{0.5n_1}{n_1}\right)^2 = \underline{2265.6 \text{ lb-ft}}$$

(c)

$$\frac{T_1}{T_2} = \frac{[B_p I_a]_1}{[B_p I_a]_2} \quad \Rightarrow \quad \frac{9062.5}{2265.6} = \frac{B_p \times 1675}{B_p \times I_{a2}}$$

$$I_{a2} = 418.75 \text{ A}$$

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{\text{acir}}}{\Phi}\right]_1 \times \left[\frac{\Phi}{V_T - I_a R_{\text{acir}}}\right]_2$$

$$V_2 = \frac{n_2}{n_1} \times \frac{\Phi_2}{\Phi_1} \times [V_T - I_a R_{\text{acir}}]_1 + I_{a2} R_{\text{acir}\,2}$$

$$V_2 = \frac{0.5n_1}{n_1} \times \frac{\Phi_1}{\Phi_1} \times [750 - 1675 \times 0.0096] + 418.75 \times 0.0096$$

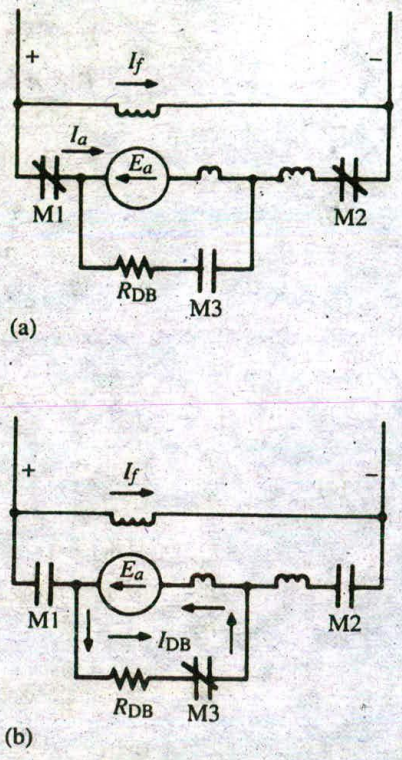
$$V_2 = \underline{371.0 \text{ V}}$$

11.11 DYNAMIC BRAKING, PLUGGING, AND JOGGING

Direct-current motors may be decelerated quickly by converting the energy stored in the moving masses to electrical energy and dissipating it as heat through resistors. To do this, the motor armature is disconnected from the supply lines and connected across a suitable resistor while the shunt field is maintained at full strength. The motor behaves as a generator and feeds current to the resistor, dissipating heat at a rate equal to I^2R. The heat power rating of the resistor is determined by the material used and its physical dimensions. The value of R is generally selected to provide an armature current that will approximate 150 to 300 percent rated current. In accordance with Lenz's law, the armature current produced by dynamic braking will be in a direction to oppose the motion of the armature. It is this negative torque, or countertorque, that slows the machine. Dynamic braking is also very useful for limiting the speed of overhauling loads, such as would be produced by lowering heavy loads on elevators and winches or by electric trains going downgrade. Since the energy is expended in resistors, this type of braking is sometimes referred to as *resistive braking*.

A dynamic-braking circuit for a compound motor is shown in Figure 11.11. Figure 11.11(a) shows normal motor operations; contactors M1 and M2 are closed and

FIGURE 11.11
Compound motor with a dynamic-braking loop: (a) normal motor operation; (b) dynamic-braking loop.



contactor M3 is open. To apply dynamic braking, contactors M1 and M2 are opened and contactor M3 is closed. This is shown in Figure 11.11(b). Note that *the series field is not included in the dynamic-braking (DB) loop.* To include it would result in a differential connection; the current in the series field would set up an mmf in opposition to the shunt field mmf, causing a lower E_a, and hence a smaller braking effect.

When sufficiently slowed, the motor circuit is opened, and a mechanical brake is applied to bring the machine to a full stop and to prevent further rotation. A typical magnetically released spring-loaded holding brake is shown in Figure 11.12.

Regenerative Braking

Regenerative braking converts the energy of overhauling loads into electrical energy and pumps it back into the electrical system. An overhauling load will drive a DC motor faster than it would normally run with a given applied voltage. This will cause its cemf to become greater than the applied voltage and result in generator action. Regenerative braking is used extensively in electrified railroads and to some extent with elevators and winches. Regenerative braking cannot occur in the series motor unless the field is connected across the line with a current-limiting resistor in series, or by separately exciting the series field from a low-voltage DC generator.

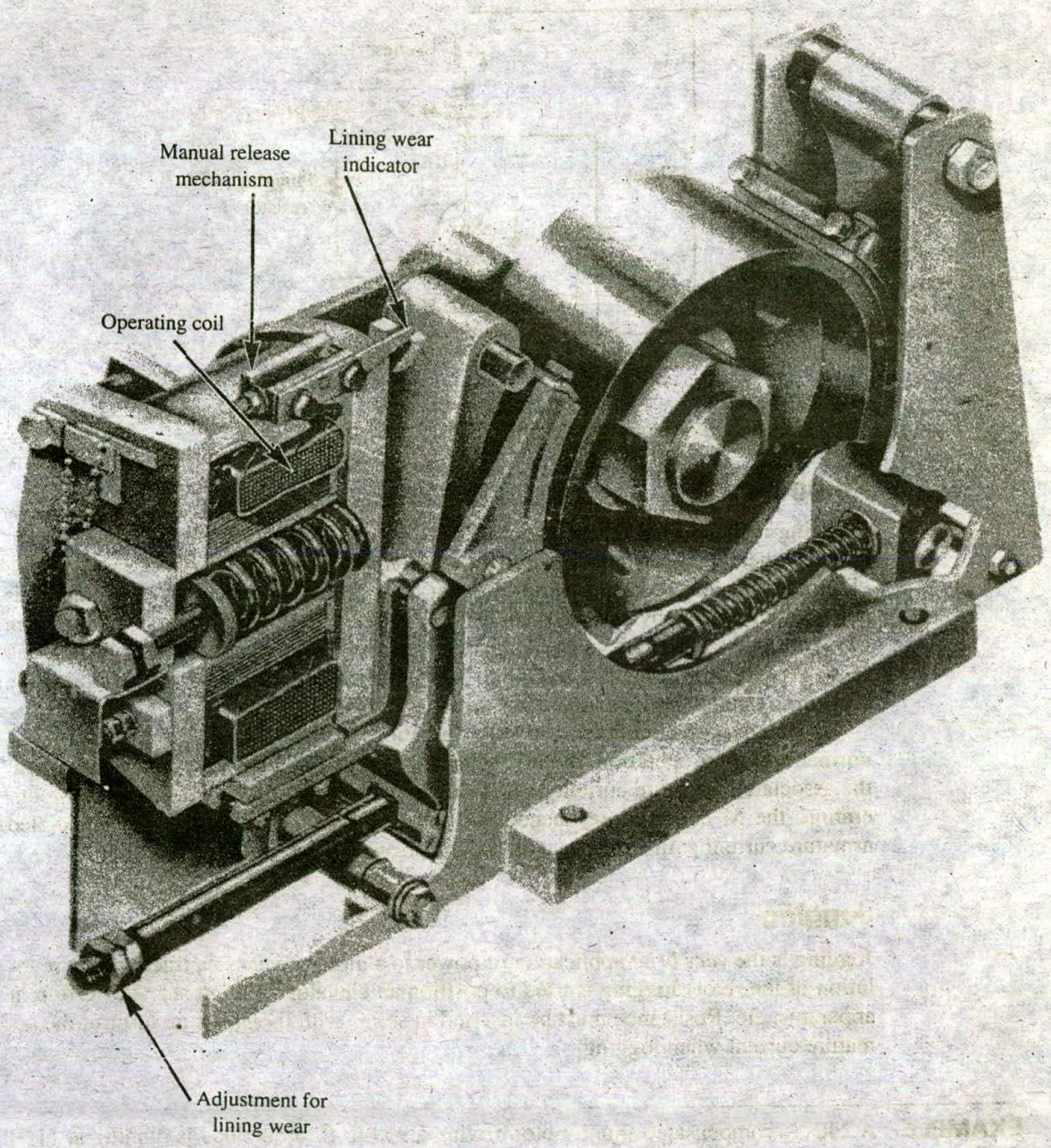


FIGURE 11.12
Magnetically released spring-loaded holding brake. (Courtesy GE Industrial Systems)

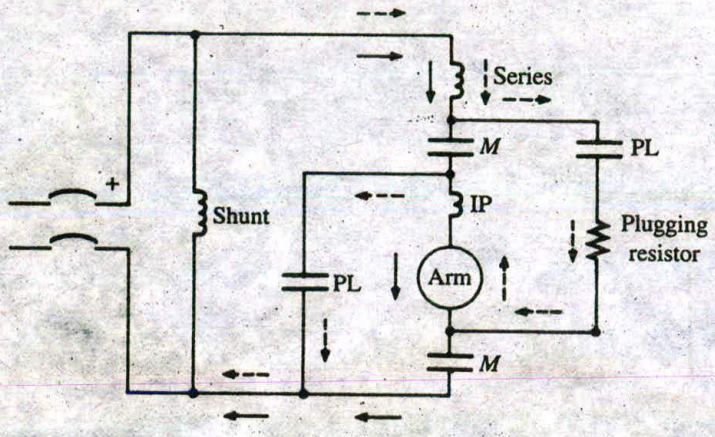


FIGURE 11.13
Simplified circuit for plugging operations.

Plugging

Plugging is the electrical reversal of a motor before it stops. It is used in those applications where a motor must be brought to an emergency stop, a quick reversal, or to eliminate the long coasting time inherent in high-inertia machines. The motor is switched to reverse by *reversing the voltage applied to the armature.* The current in the series and shunt fields must not be reversed. Sufficient resistance must be inserted in series with the armature circuit to prevent excessive current from tripping the breaker or damaging the commutator–brush interface.

A simplified circuit for plugging operations is shown in Figure 11.13. During normal motoring operation, the M contacts are closed and the PL contacts are open; the associated armature current path is shown with solid arrows. During plugging operation, the M contacts are opened and the PL contacts are closed; the associated armature current path is shown with broken arrows.

Jogging

Jogging is the *very brief* application of power to a motor, to cause a fraction of a revolution of the rotor. Jogging is used to position an elevator, to align shafts of different apparatus, etc. Resistance must be inserted in series with the armature to limit the armature current when jogging.

EXAMPLE 11.7 A 240-V, compensated shunt-motor driving a 910-lb-ft torque load is running at 1150 r/min. The efficiency of the motor at this load is 94.0 percent. The combined armature, compensating winding, and interpole resistance is 0.00707 Ω, and the resistance of the shunt field is 52.6 Ω. Determine the resistance of a dynamic-braking resistor that will

be capable of developing 500 lb-ft of braking torque at a speed of 1000 r/min. Assume windage and friction at 1000 r/min are essentially the same as at 1150 r/min.

Solution

The dynamic braking circuit is similar to that in Figure 11.11(b).

$$P_{\text{shaft}} = \frac{T \times n}{5252} = \frac{910 \times 1150}{5252} = 199.257 \text{ hp}$$

$$P_{\text{in}} = \frac{P_{\text{shaft}}}{\eta} = \frac{199.257 \times 746}{0.940} = 158{,}134 \text{ W}$$

$$P_{\text{in}} = V_T I_T \quad \Rightarrow \quad 158{,}134 = 240 \times I_T \quad \Rightarrow \quad I_T = 658.89 \text{ A}$$

$$I_f = \frac{V_T}{R_f} = \frac{240}{52.6} = 4.56 \text{ A}$$

$$I_a = I_T - I_f = 658.89 - 4.56 = 654.33 \text{ A}$$

$$V_T = E_{a1} + I_{a1} R_{\text{acir}} \quad \Rightarrow \quad 240 = E_{a1} + 654.33 \times 0.00707$$

$$E_{a1} = 235.37 \text{ V}$$

Since the flux density remains constant;

$$\frac{T_1}{T_2} = \frac{[B_p I_a]_1}{[B_p I_a]_2} \quad \Rightarrow \quad \frac{910}{500} = \frac{654.33}{I_{a2}} \quad \Rightarrow \quad I_{a2} = 359.52 \text{ A}$$

$$\frac{E_{a1}}{E_{a2}} = \frac{[n \Phi_p k_G]_1}{[n \Phi_p k_G]_2} \quad \Rightarrow \quad \frac{235.37}{E_{a2}} = \frac{1150}{1000}$$

$$E_{a2} = 204.67 \text{ V}$$

Referring to Figure 11.11(b),

$$E_{a2} = I_{a2}(R_{\text{acir}} + R_{\text{DB}}) \quad \Rightarrow \quad 204.67 = 359.52(0.00707 + R_{\text{DB}})$$

$$R_{\text{DB}} = \underline{0.562 \ \Omega}$$

11.12 STANDARD TERMINAL MARKINGS AND CONNECTIONS OF DC MOTORS

The standard terminal markings for DC motors and the proper connections for different directions of rotation are shown in Figure 11.14 [2]. The directions of rotation are as viewed from the end opposite the drive shaft. Differential connections are not shown. However, because of the hazards inherent in a differential connection, compound motors with unmarked terminals must be tested to determine the relative polarity of the shunt and series windings, and the leads must be appropriately marked, before connecting the motor to a starter. A test procedure to determine the relative polarity of the series and shunt fields is detailed in Reference [1].

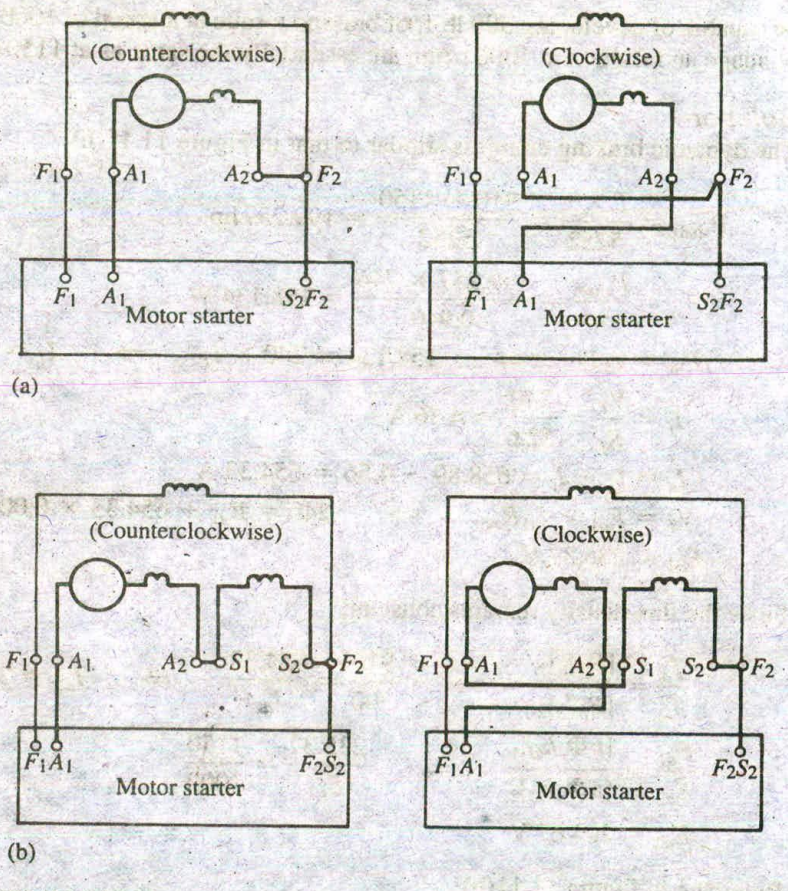


FIGURE 11.14
NEMA standard terminal markings for DC motors, and proper connections for different directions of rotation: (a) shunt motor; (b) compound motor.

SUMMARY OF EQUATIONS FOR PROBLEM SOLVING

$$\mathcal{F}_{net} = \mathcal{F}_f + \mathcal{F}_s - \mathcal{F}_d \tag{11–1}$$

$$T_D = B_p I_a k_M \tag{10–17}$$

$$n = \left.\frac{V_T - I_a R_{acir}}{\Phi_p k_G}\right|_{\Phi_p \neq 0} \tag{10–26}$$

$$\frac{T_{D1}}{T_{D2}} = \frac{[B_p I_a]_1}{[B_p I_a]_2} \tag{11–2}$$

$$\frac{n_1}{n_2} = \frac{\left[\dfrac{V_T - I_a R_{\text{acir}}}{\phi_p k_G}\right]_1}{\left[\dfrac{V_T - I_a R_{\text{acir}}}{\phi_p k_G}\right]_2}, \qquad \phi \neq 0 \tag{11–3}$$

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{\text{acir}}}{B_p}\right]_1 \times \left[\frac{B_p}{V_T - I_a R_{\text{acir}}}\right]_2, \qquad \phi \neq 0 \tag{11–4}$$

Linear Assumption

$$\frac{T_{D1}}{T_{D2}} = \frac{[\mathcal{F}_{\text{net}} I_a]_1}{[\mathcal{F}_{\text{net}} I_a]_2} \tag{11–6}$$

$$\frac{n_1}{n_2} = \left[\frac{V_T - I_a R_{\text{acir}}}{\mathcal{F}_{\text{net}}}\right]_1 \times \left[\frac{\mathcal{F}_{\text{net}}}{V_T - I_a R_{\text{acir}}}\right]_2, \qquad \phi \neq 0 \tag{11–7}$$

$$T_{D,\text{series}} \propto \mathcal{F}_s I_a \cdot I_a \propto I_a^2 \tag{11–8}$$

SPECIFIC REFERENCES KEYED TO TEXT

1. Hubert, C. I. *Preventive Maintenance of Electrical Equipment.* Prentice Hall, Upper Saddle River, NJ, 2002.
2. National Electrical Manufacturers Association. *Motors and Generators.* NEMA Standards Publication No. MG-1-1998, NEMA, Rosslyn, VA, 1999.

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Kloeffler, R. G., R. M. Kerchner, and J. L. Brenneman. *Direct-Current Machinery.* Macmillan, New York, 1949.

Langsdorf, A. S. *Principles of Direct-Current Machines.* McGraw-Hill, New York, 1959.

Smeaton, R. W. *Motor Application and Maintenance Handbook,* 2nd ed. McGraw-Hill, New York, 1987.

REVIEW QUESTIONS

1. Explain why some shunt motors require a stabilizing winding.
2. How does a compound motor differ in construction from a stabilized-shunt motor?
3. Sketch the circuit for a compound motor and indicate (with broken lines) on the diagram the correct connections to reverse the motor.

4. Approximately what percent of total mmf is supplied by the series field in (a) stabilized-shunt motors; (b) compound motors?
5. State an application that is specifically appropriate for (a) shunt motors; (b) series motors; (c) compound motors.
6. Explain why a series motor self-destructs due to overspeed when the load is removed.
7. Is there any difference between the rated torque developed by a compound motor and the rated torque developed by a shunt motor of equal power and speed ratings? Explain.
8. Explain how compound motors smooth the energy demand required by a pulsating load such as a flywheel punch press.
9. Explain why a differential connection of a compound motor should be avoided.
10. A 20-hp, 230-V compound motor is supplied with both an armature rheostat and a shunt field rheostat for speed control. The shunt field rheostat has a resistance range of zero to 300 Ω. The armature rheostat has a range of zero to 1.5 Ω. When the machine is started from standstill, what should the numerical value of resistance be in each rheostat? Justify your answer with a theoretical explanation.
11. Sketch the circuit diagram, and explain the operation of the Ward–Leonard system with respect to speed adjustment and reversing.
12. Differentiate between regenerative braking and resistive braking, and state an application for each.
13. Differentiate between plugging and jogging, and state an application for each.

PROBLEMS

11–1/7 A compensated shunt motor rated at 60 hp, 240 V, 400 r/min, draws 209.1 A when operating at rated conditions. The motor parameters are $R_{acir} = 0.0483\ \Omega$, $R_f = 39.1\ \Omega$, and $N_f = 1476$ turns/pole. The corresponding magnetization curve is shown in Figure 11.15. (a) Determine the resistance of an external resistor required in series with the shunt field to raise the speed to 600 r/min. Assume the new torque load is 40 percent rated torque. (b) Determine the new armature current; (c) power rating of the resistor.

11–2/7 A 75-hp, 240-V, 250-r/min compensated shunt motor has the following parameters: $R_{acir} = 0.0665\ \Omega$, $R_f = 25.6\ \Omega$, and $N_f = 835$ turns/pole. The corresponding magnetization curve is shown in Figure 11.15. The machine has an efficiency of 86.4 percent when operating at rated conditions. Determine the resistance and power rating of an external resistor required in series with the shunt field to raise the speed to 500 r/min. Assume a constant shaft-power load and no change in efficiency.

11–3/7 A 150-hp, 240-V, 650 r/min compensated shunt motor has the following parameters: $R_a = 0.00872\ \Omega$, $R_{IP} + R_{CW} = 0.0038\ \Omega$, $R_f = 32.0\ \Omega$, and $N_f = 1143$ turns/pole. The efficiency at rated load is 92.0 percent. The corresponding magnetization curve is shown in Figure 11.15. (a) Determine the external resistance required in series with the shunt field that will pro-

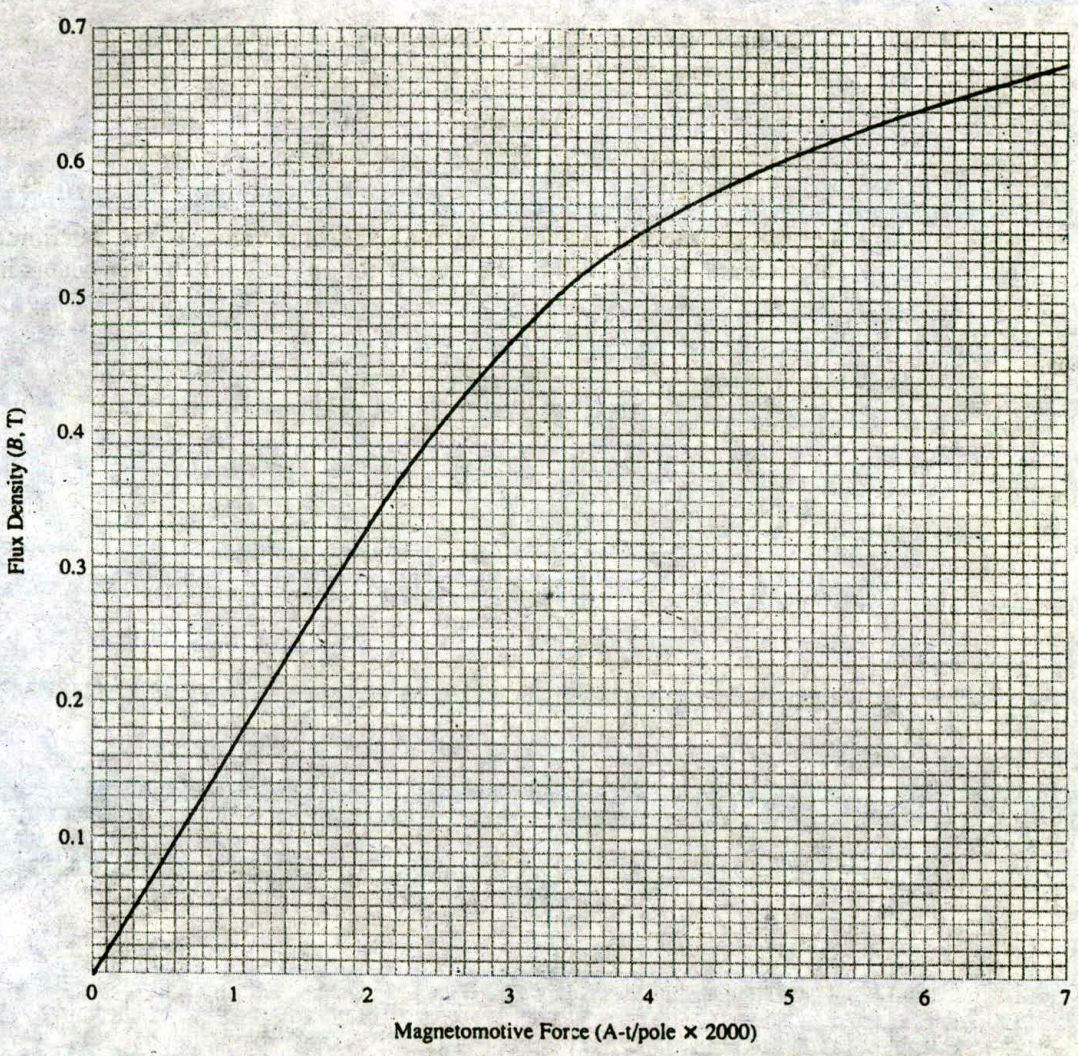


FIGURE 11.15
Magnetization curve for Problems 11–1/7 to 11–4/7.

vide a no-load speed of 2100 r/min. Assume the motor current at no-load is 18.4 A. (b) Determine the power rating of the resistor.

11–4/7 A 50-hp, 240-V, 1750 r/min compensated shunt motor operating at rated load has an efficiency of 88.7 percent. The machine parameters are $R_a = 0.0287\ \Omega$, $R_{IP} = 0.0138\ \Omega$, $R_f = 67.4\ \Omega$, and $N_f = 1850$ turns/pole. The corresponding magnetization curve is shown in Figure 11.15. (a) Determine the external resistance required in series with the armature in order to obtain a speed of 1024 r/min. Assume the machine is operating with 65 percent rated torque. (b) Determine the power rating of the resistor.

11–5/7 A 700-hp, 850 r/min, 500-V compound motor has an efficiency of 93.2 percent when operating at rated conditions. The motor parameters are:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.00689	0.001374	0.000687	72.5
Turns/pole	—	—	6	995

The magnetization curve for the motor is shown in Figure 11.16. Determine (a) percent mmf supplied by the series field; (b) speed if an open occurs in

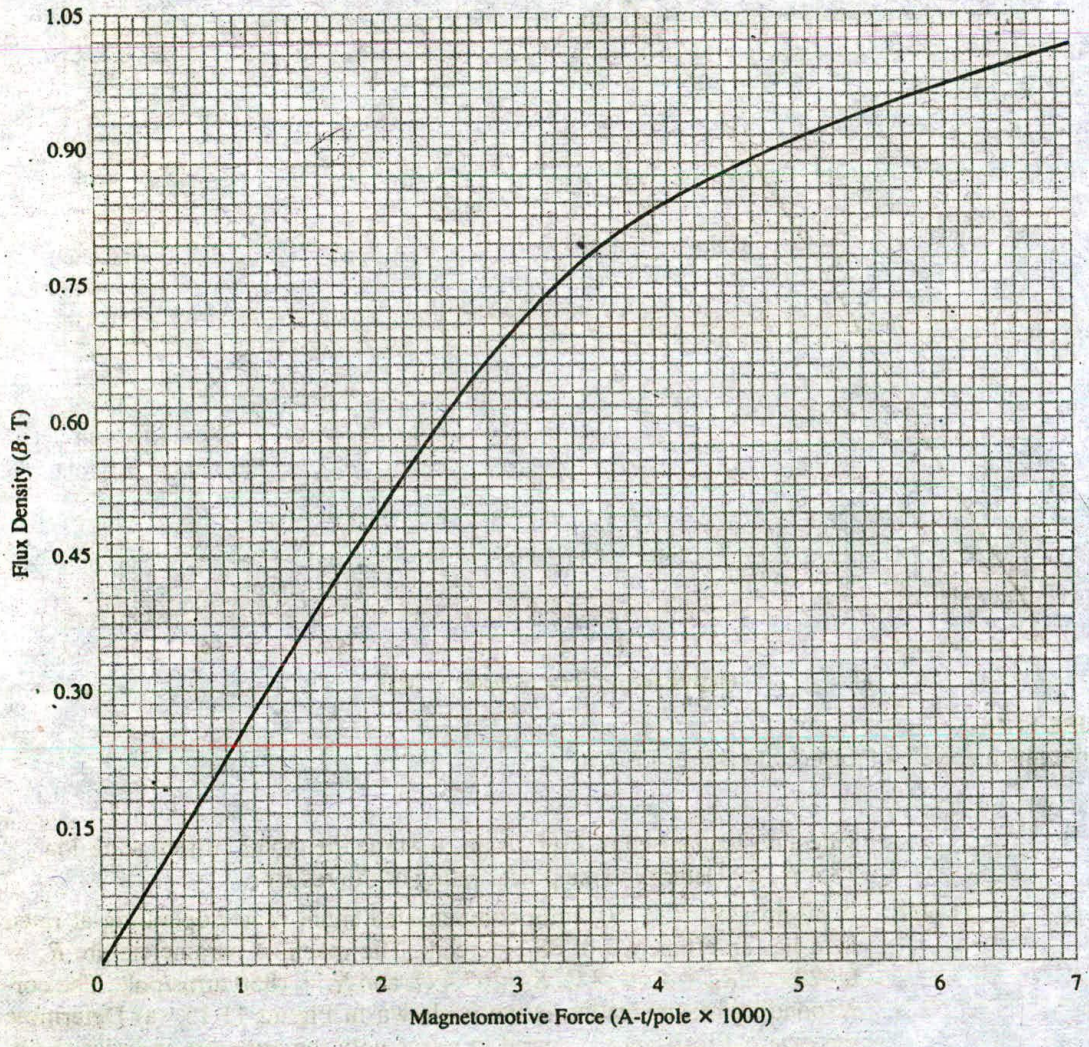


FIGURE 11.16
Magnetization curve for Problems 11–5/7 to 11–11/7.

the shunt field circuit. Assume the connected load is such that the armature current rises to 1540 A.

11–6/7 A 40-hp, 1150 r/min compensated shunt motor operating from a 240-V system is supplying a load whose torque varies directly as the speed. The efficiency of the motor at rated conditions is 90.2 percent, and the motor parameters are:

	Armature	IP + CW	Shunt
Resistance, Ω	0.0680	0.0289	99.5
Turns/pole	—	—	1231

The magnetization curve is shown in Figure 11.16. Determine the external resistance required in series with the shunt field circuit in order to operate at 125 percent rated speed.

11–7/7 A 400-hp, 250-V, 100 r/min compound motor with a compensating winding has an efficiency of 89.8 percent when operating at rated conditions. The motor parameters are:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.002660	0.000774	0.000356	24.1
Turns/pole	—	—	2	400

The magnetization curve is shown in Figure 11.16. Determine (a) motor current; (b) armature current; (c) mechanical power developed. (d) If the torque required to start the machine is 115 percent rated torque, the machine is to be operated without its series field, and the armature current is limited to 200 percent rated armature current, will the motor start?

11–8/7 A 50-hp, 230-V, 500 r/min compound motor with a compensating winding has the following parameters:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.071	0.0140	0.031	75
Turns/pole	—	—	6	1000

The magnetization curve is shown in Figure 11.16. The motor is operating at rated conditions and draws a line current of 190 A. Determine (a) cemf; (b) mechanical power developed; (c) rated shaft torque; (d) mechanical power required to overcome rotational losses. (e) Assuming a constant-torque load, determine the speed if the series field is not used.

11–9/7 A 60-hp, 468 r/min, 240-V stabilized-shunt motor has an efficiency of 89.0 percent when operating at rated conditions. The motor parameters are:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.0342	0.00924	0.00308	71.6
Turns/pole	—	—	1.5	1268

The magnetization curve is shown in Figure 11.16. Sketch the motor circuit and determine (a) rated motor current; (b) rated field current; (c) rated

armature current; (d) rated shaft torque; (e) external resistance required in order to limit the locked-rotor armature current to 200 percent of its rated value; (f) additional series field turns of the same size conductor required to cause a 135 percent increase in locked-rotor torque, assuming armature current is limited to 200 percent rated armature current; (g) new steady-state speed, assuming additional series field turns, the motor is loaded to rated armature current, and no external resistance is inserted in series with the shunt or series field.

11–10/7 A 75-hp, 850 r/min, 500-V series motor has an efficiency of 90.2 percent when operating at rated conditions. The series field has 30 turns/pole, and the motor parameters are:

	Armature	IP + CW	Series
Resistance, Ω	0.1414	0.0412	0.0189

The motor has a maximum safe speed of 1700 r/min. Is it safe to operate the motor with a 10-hp shaft load? Use the magnetization curve in Figure 11.16, and show all work. Neglect changes in windage and friction.

11–11/7 A series motor rated at 150 hp, 400 r/min, and 240 V is used to drive a load that cycles between 120 percent rated power and 40 percent rated power. The equivalent demagnetizing mmf due to armature reaction is approximately equal to 7.5 percent of the series field mmf. The series field has 12 turns/pole, the efficiency at rated load is 93.2 percent, and the motor parameters are:

	Armature	Interpole	Series
Resistance, Ω	0.01346	0.00392	0.00181

Determine the upper and lower speeds. Use the magnetization curve in Figure 11.16.

11–12/8 A 240-V, 50-hp, 1150 r/min compound motor has the following parameters:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.0673	0.0196	0.00902	85.6
Turns/pole	—	—	8	750

The efficiency at rated load is 88.7 percent. Determine the speed if a 20-Ω resistor is inserted in series with the shunt field, and the resultant speed causes an armature current of 200 A. Neglect saturation effects.

11–13/8 A 15-hp, 2500 r/min, 240-V compound motor draws 58.6 A when operating at rated conditions. The motor parameters are:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.241	0.0700	0.322	138
Turns/pole	—	—	10	1360

If a 1.6-Ω resistor is connected in series with the armature, a 100-Ω resistor is connected in series with the shunt field, the load on the shaft is such as to

cause the motor to draw 40 A from the line, and saturation effects are neglected, determine (a) speed; (b) mechanical power developed; (c) developed torque.

11–14/8 A 240-V, 30-hp, 650 r/min compound motor has an efficiency of 94.2 percent when operating at rated conditions. The motor parameters are:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.1192	0.0347	0.0159	80
Turns/pole	—	—	7	513

Neglecting the effects of saturation, determine (a) speed at rated armature current if the series field is not used; (b) speed at rated armature current if the series field is differentially connected.

11–15/8 A 240-V, 20-hp, 300 r/min stabilized-shunt motor with an efficiency of 84.3 percent has the following parameters:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.168	0.0490	0.0226	100
Turns/pole	—	—	1.5	1096

Neglecting the effects of saturation, determine (a) speed at no load, assuming the no-load motor current is 15 A; (b) speed regulation in (a); (c) developed torque at 60 percent rated armature current.

11–16/8 A 100-hp, 3500 r/min, 240-V compound motor has an efficiency at rated load of 94.6 percent. The motor parameters are:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.0358	0.0104	0.00480	52.3
Turns/pole	—	—	3	367

Neglecting the effects of saturation, determine (a) speed, if the load on the shaft is decreased to a value that results in a line current of 136 A; (b) developed torque for conditions in (a).

11–17/10 A coal conveyer is driven by a separately excited stabilized-shunt motor through an adjustable-voltage drive system. The coal conveyer is a constant-torque load on the motor. The motor armature is rated at 700 hp, 400 r/min, 250 V, 2230 A. The field is excited from a constant voltage 120-V DC supply. The motor parameters are:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.006294	0.001831	0.000843	10.8

Determine the applied armature voltage when operating at 100 r/min.

11–18/10 A DC adjustable-voltage drive system is used to drive a reel in a steel mill. As steel is wound on the reel, the reel diameter increases, increasing the torque load on the motor. To maintain constant power, the speed must vary inversely with the torque. In effect, the reel represents a constant-power

load. The motor driving the reel is a stabilized-shunt motor rated at 1000 hp, 500 V, and draws an armature current of 1522 A at 400 r/min. The shunt field is separately excited through a rectifier from a 120-V, 60-Hz system. The motor parameters are:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.0115	0.00179	0.00156	15.76

Determine the applied armature voltage when operating at 700 r/min.

11–19/11 A separately excited shunt motor with a compensating winding, rated at 550 V, 400 hp, has a base speed of 1750 r/min. The shunt field is separately excited from a 120-V DC supply. The efficiency of the motor, less the shunt field, is 94.6 percent when operating at rated conditions. The motor parameters are:

	Armature	IP + CW	Shunt
Resistance, Ω	0.0192	0.00573	28

Assume the machine is operating at rated conditions when an overheated bearing starts to smoke. The armature is disconnected from the supply line and connected to a dynamic-braking resistor. The inertia of the load prevents an instantaneous slowing of the machine, and 200 percent rated torque is developed when the dynamic-braking circuit is closed. Determine the resistance of the dynamic-braking resistor. The circuit is shown in Figure 11.11(b).

11–20/11 A 150-hp, 1750 r/min, 240-V compensated shunt motor is operating at rated conditions with an efficiency of 92.3 percent. The motor parameters are:

	Armature	IP + CW	Shunt
Resistance, Ω	0.0233	0.0099	33.9

Determine the armature current at 500 r/min when dynamic braking through a 0.324-Ω resistor. The circuit is shown in Figure 11.11(b).

12

Direct-Current Generator Characteristics and Operation

12.1 INTRODUCTION

This chapter deals primarily with self-excited generators, their characteristics, operation, and problems, and builds on the theory developed in Chapter 10.

Although the expanded use of solid-state converters and control systems has reduced the demand for direct-current generators, they still have applications in steel mills, ice-breaking vessels, the electrochemical industry, and as a low-ripple DC source for some drive systems.

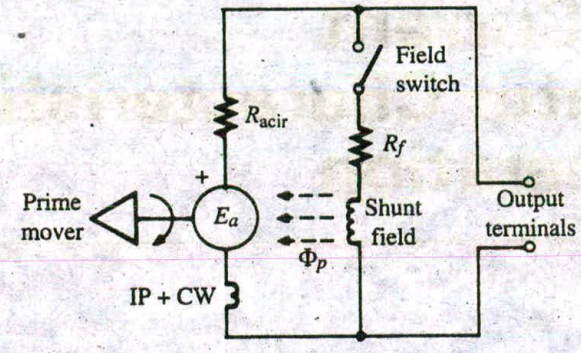
12.2 SELF-EXCITED SHUNT GENERATORS

A self-excited shunt generator whose equivalent circuit is shown in Figure 12.1(a) develops its initial emf from residual magnetism in the pole iron.[1] The switch shown in the field circuit is used only as an aid in the explanation of voltage buildup; field switches are rarely used with self-excited generators.

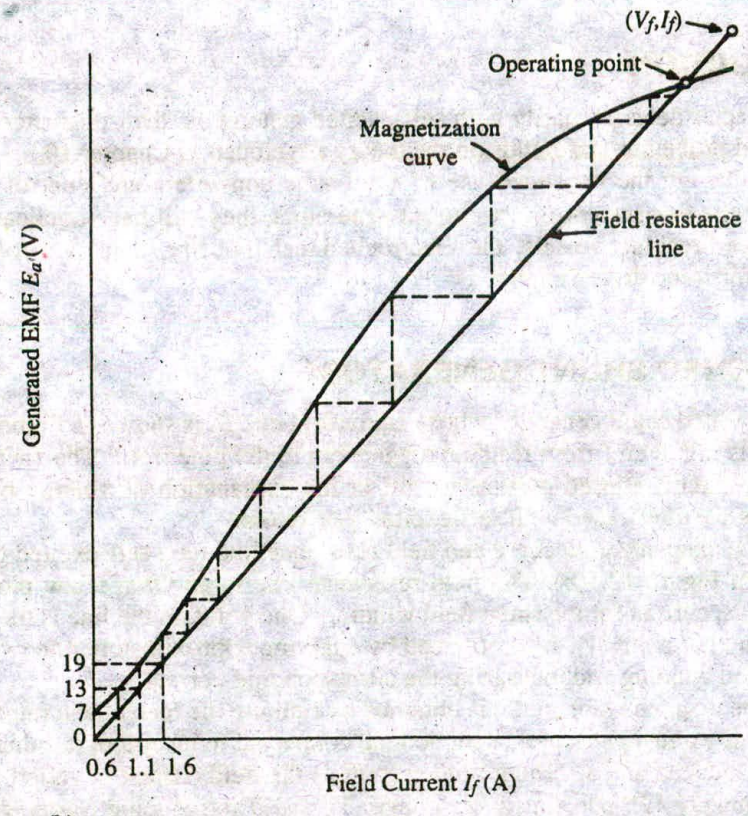
The magnetization curve and field resistance line for a self-excited generator are shown in Figure 12.1(b). The field-resistance line is an Ohm's law plot of applied voltage vs. current for the shunt field winding. One point on the line is the origin (0 V, 0 A). Another point (V_f, I_f) is obtained by applying approximately rated voltage to the shunt field winding and measuring the corresponding current.

The magnetization curve is obtained by running the machine at rated speed, *as a separately excited generator,* with no load connected to its output terminals, and plotting the induced emf vs. shunt field current as the field current is varied from zero to approximately 125 percent rated voltage. To avoid introducing hysteresis loops, the

[1]The magnetic retentivity of the pole iron in self-excited generators provides sufficient residual flux to generate approximately 5 percent rated voltage when operating at rated speed with the field switch open.



(a)



(b)

FIGURE 12.1
(a) Circuit diagram of a self-excited shunt generator; (b) illustration of voltage buildup in a self-excited shunt generator.

field current should not be decreased at any time during the test. If a planned test point is overshot, either start all over, or skip that point. The curve can be easily plotted on an *X-Y* plotter.

Voltage Buildup

Assuming the field switch in Figure 12.1(a) is open and the armature is rotating at rated speed, the residual magnetism will cause the voltage to build up to about 7 V. This is shown on the magnetization curve in Figure 12.1(b). Closing the field switch impresses 7 V across the field winding, causing a current of 0.6 A as shown on the field-resistance line. The 0.6 A of field current causes the voltage to increase to 13 V, as shown on the magnetization curve. The 13 V causes 1.1 A in the field winding, causing a further rise in voltage to 19 V, and so forth. The voltage continues to rise until a further increase in voltage no longer causes an increase in flux. This occurs at the intersection of the magnetization curve with the field-resistance line and is called the *operating point.* As the intersection is approached, the increment increase in emf gets less for a given increment increase in field current, and the buildup tapers off to a final value of generated emf and field current. Although described as a step-by-step process, the actual buildup is a smooth and fairly rapid rise to the operating point. The buildup of voltage is limited by magnetic saturation and the resistance of the field circuit.

Adjusting the No-Load Voltage

Adjusting the no-load voltage, also called *open-circuit voltage,* is accomplished by changing the slope of the field-resistance line.

Adding resistance in series with the shunt field increases the slope of the line, causing the point of intersection, and hence the operating point, to occur at a lower voltage. A family of field-resistance lines and the corresponding operating points (intersections) are shown in Figure 12.2 for different rheostat settings, where

$$R = R_f + R_{\text{rheo}}$$

The operating points in Figure 12.2 are the graphical solutions of two simultaneous equations: the magnetization curve, expressed as

$$E_a = n\Phi_p k_G = n\left(\frac{N_f I_f}{\mathcal{R}}\right)k_G \qquad \textbf{(12–1)}$$

and the field resistance line, expressed as

$$E_a = I_f(R_f + R_{\text{rheo}}) \qquad \textbf{(12–2)}$$

A graphical solution is used because the nonlinear nature of the reluctance $\mathcal{R}$ in Eq. (12–1) makes an algebraic solution very difficult.

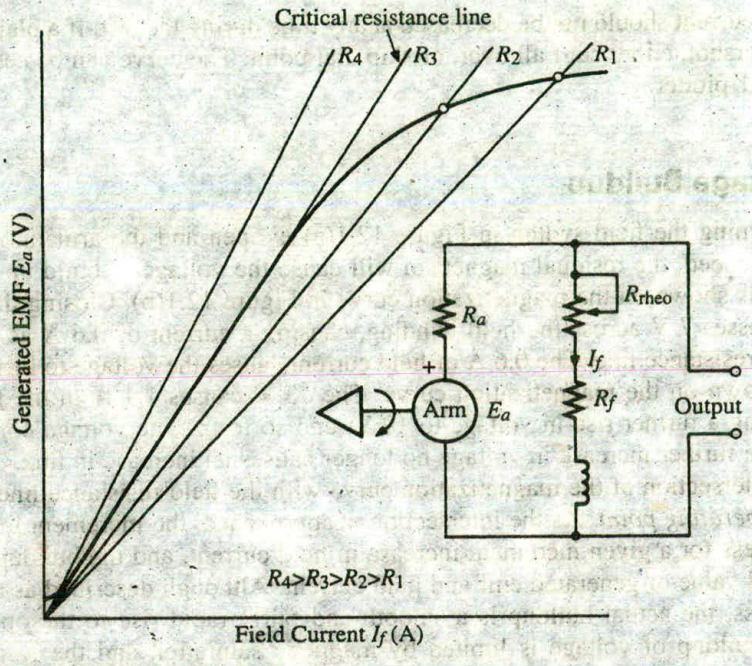


FIGURE 12.2
Family of field-resistance lines and corresponding operating points.

If the rheostat resistance is adjusted to a value that causes the field-resistance line to be to the left of the straight line portion of the magnetization curve, R_4 in Figure 12.2, the buildup of generator voltage will be only slightly higher than the value obtained by residual magnetism alone.

If the field-resistance line is coincident with the linear section of the magnetization curve, the voltage will be unstable and can assume any value along the coincident section. The value of field-circuit resistance that causes coincidence is called the *critical resistance.* To build up voltage, the field-circuit resistance must be less than the critical value. Thus an open in the field rheostat, too high a rheostat resistance, low brush pressure on the commutator, dirty brushes and/or commutator, or an open in the shunt field coils will prevent the buildup of voltage.

Basic Design

Self-excited generators are usually designed to obtain approximately 125 percent of rated voltage with the rheostat set for zero resistance and no load connected to the output terminals. The field rheostat is designed so that maximum rheostat resistance will limit the no-load voltage to approximately 50 percent of rated voltage.

12.3 EFFECT OF SPEED ON VOLTAGE BUILDUP OF A SELF-EXCITED GENERATOR

The critical resistance of a self-excited generator is closely related to the speed of the machine. A machine running at low speed will not build up to the same voltage as when running at a higher speed, using the same field-circuit resistance. Hence, the critical resistance will be different for different machine speeds. This is illustrated in Figure 12.3. For the field-resistance line shown, the intersection with the magnetization curve for high speed occurs at a relatively high voltage and the intersection with the magnetization curve for low speed occurs at a value of voltage slightly higher than that produced by the residual flux.

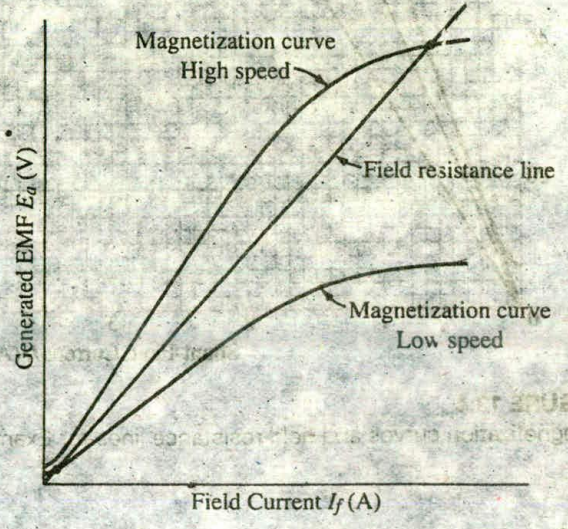
EXAMPLE 12.1 The magnetization curve for a certain self-excited, 125-V, 50-kW, 1750 r/min shunt generator is shown in Figure 12.4. The no-load voltage with the rheostat shorted is 156 V. Determine (a) field-circuit resistance; (b) field-rheostat setting that will provide a no-load voltage of 140 V; (c) armature voltage if the rheostat is set to 14.23 Ω; (d) field-rheostat setting that will cause critical resistance; (e) armature voltage at 80 percent rated speed, and the rheostat shorted; (f) rheostat setting required to obtain a no-load armature voltage of 140 V at 1750 r/min *if the shunt field is separately excited* from a 120-V DC source.

Solution

(a) From the magnetization curve in Figure 12.4, the shunt field current that corresponds to a no-load voltage of 156 V is ≈4.7 A. Thus,

$$R_f = \frac{E_a}{I_f} = \frac{156}{4.7} = 33.1915 \quad \Rightarrow \quad \underline{33.19\ \Omega}$$

FIGURE 12.3
Effect of speed on voltage buildup in a self-excited generator.



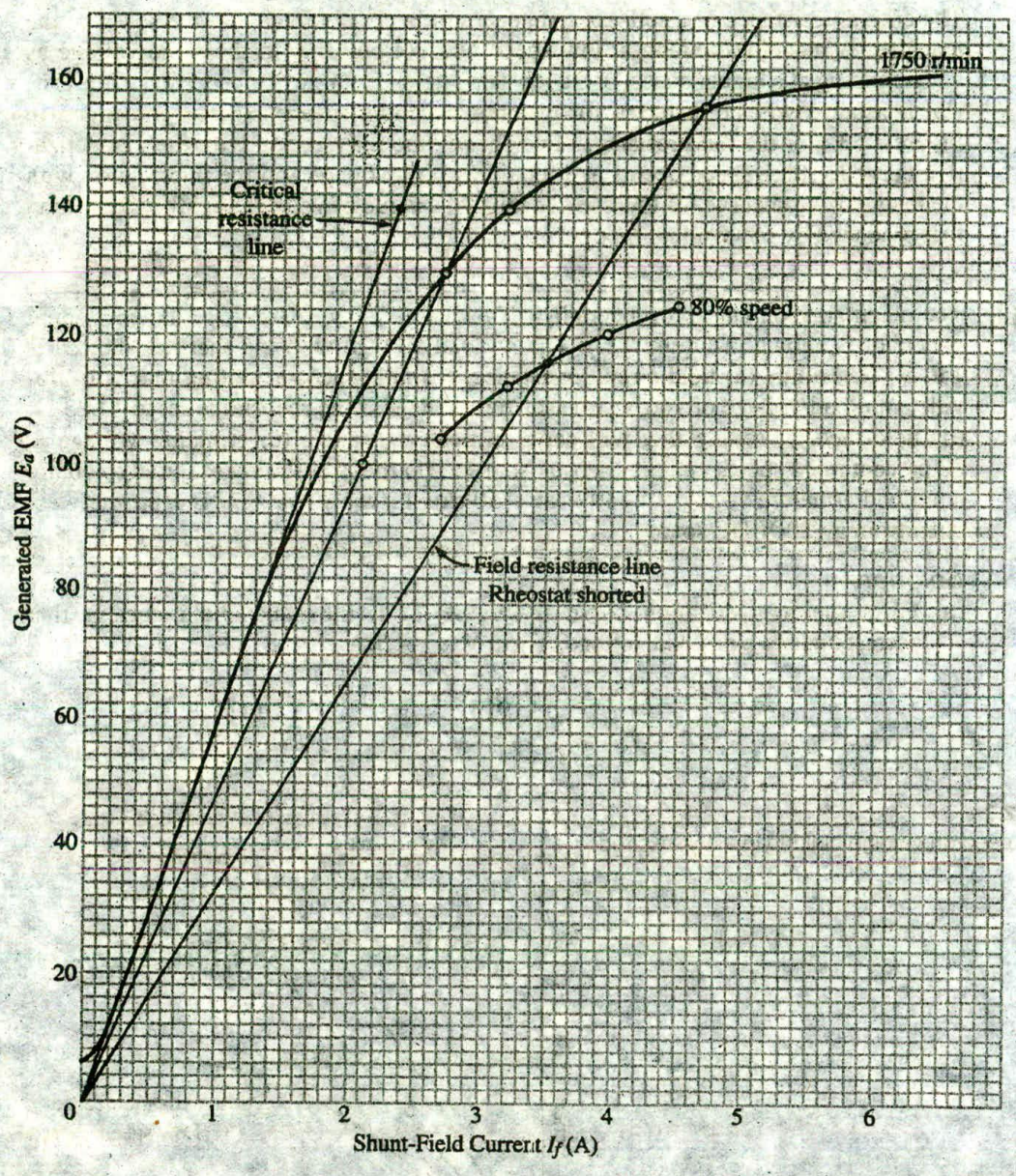


FIGURE 12.4
Magnetization curves and field-resistance lines for Example 12.1.

(b) From the magnetization curve, the field current that corresponds to a no-load voltage of 140 V is ≈3.2 A.

$$I_f = \frac{E_a}{R_f + R_{\text{rheo}}} \quad \Rightarrow \quad R_{\text{rheo}} = \frac{E_a}{I_f} - R_f$$

$$R_{\text{rheo}} = \frac{140}{3.2} - 33.19 = \underline{10.56\ \Omega}$$

(c)

$$R_f + R_{\text{rheo}} = 33.19 + 14.23 = 47.42\ \Omega$$

The operating voltage is determined from the intersection of the magnetization curve with the *new* field-resistance line, which is plotted with data obtained from Eq. (12–2). Thus, using two arbitrary voltages (0 V and 100 V), the corresponding field currents are

$$I_f = \frac{E_a}{R_f + R_{\text{rheo}}} = \frac{0}{47.42} = 0 \text{ A}$$

$$I_f = \frac{100}{47.42} = 2.1 \text{ A}$$

Drawing a straight line through coordinates (0 V, 0 A) and (100 V, 2.1 A) results in an intersection at <u>130 V</u>.

(d) The critical field-resistance line is sketched tangent to the linear section of the magnetization curve, and the critical resistance determined from any set of coordinates. Thus, selecting

$$E_a = 140 \text{ V} \qquad I_f = 2.35 \text{ A}$$

$$R_{\text{cr}} = \frac{E_a}{I_f} = \frac{140}{2.35} = \underline{59.6\ \Omega}$$

(e) The field-resistance line is the same as for part (a). A new magnetization curve, however, must be drawn for 80 percent speed. Since only a section of the curve is needed, voltage points are calculated for several values of shunt field current on either side of the field-resistance line. The required calculation is

$$E_a \text{ at } 80\% \text{ speed} = 0.80 \times E_a \text{ at rated speed}$$

Thus,

Field Current (A)	Approximate Induced EMF (V)	
	Rated Speed	80% Rated Speed
4.50	155	124
3.95	150	120
3.20	140	112
2.70	130	104

Plotting the tabulated 80 percent speed points results in the short-section low-speed magnetization curve shown in Figure 12.4. Intersection of the field-resistance line with the low-speed magnetization curve occurs at ≈116 V.

(f) From the 1750 r/min magnetization curve, 140 V requires a field current of ≈3.2A.

$$I_f = \frac{V_f}{R_f + R_{\text{rheo}}} \quad \Rightarrow \quad R_{\text{rheo}} = \frac{V_f}{I_f} - R_f$$

$$R_{\text{rheo}} = \frac{120}{3.2} - 33.19 = \underline{4.31\ \Omega}$$

12.4 OTHER FACTORS AFFECTING VOLTAGE BUILDUP

Factors other than excessive field-circuit resistance or low speed that affect the buildup of voltage in a self-excited generator are reversed shunt field connections, reversed rotation, and reversed residual magnetism. These adverse effects can be visualized by studying the circuits in Figure 12.5 and using the right-hand rule to establish the direction of coil flux. For simplicity, only one field pole is shown. In each case:

Φ_R = flux due to residual magnetism
Φ_F = flux due to field current

Figure 12.5(a) represents normal operation; the prime-mover rotation is clockwise, and both the residual flux and the field-coil flux are directed to the left.

In Figure 12.5(b), reversed connections of the field circuit cause Φ_F to oppose Φ_R, and the voltage *builds down* from its original residual value.

In Figure 12.5(c), reversed rotation causes the armature voltage to reverse. This reverses the field current, causing Φ_F to oppose Φ_R, and the voltage builds down from its original residual value.

In Figure 12.5(d), reversed residual magnetism causes the armature voltage to reverse. This reverses the field current. In this case, both Φ_F and Φ_R are reversed. The result is voltage buildup in the reverse direction. The generator will operate at rated voltage with reversed polarity.

Correction of reversed polarity is accomplished by using an external DC source to remagnetize the iron in the correct direction. The procedure is called *field flashing* and is described in detail in Reference [1].

12.5 EFFECT OF A SHORT CIRCUIT ON THE POLARITY OF A SELF-EXCITED SHUNT GENERATOR

Under severe fault conditions, such as may occur when a self-excited shunt generator is accidentally short circuited, the very high armature current causes complete saturation of the interpole iron, making the interpole ineffective (its field strength is no

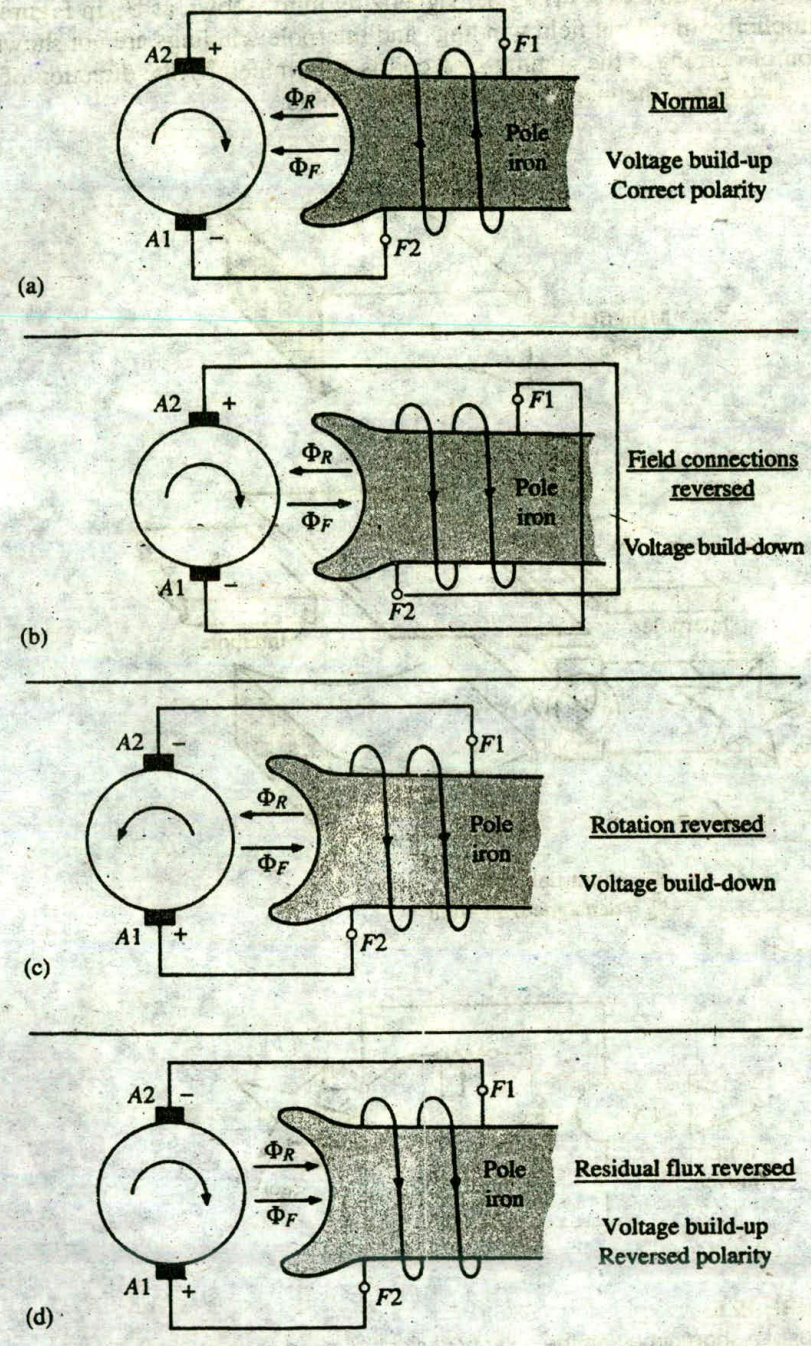
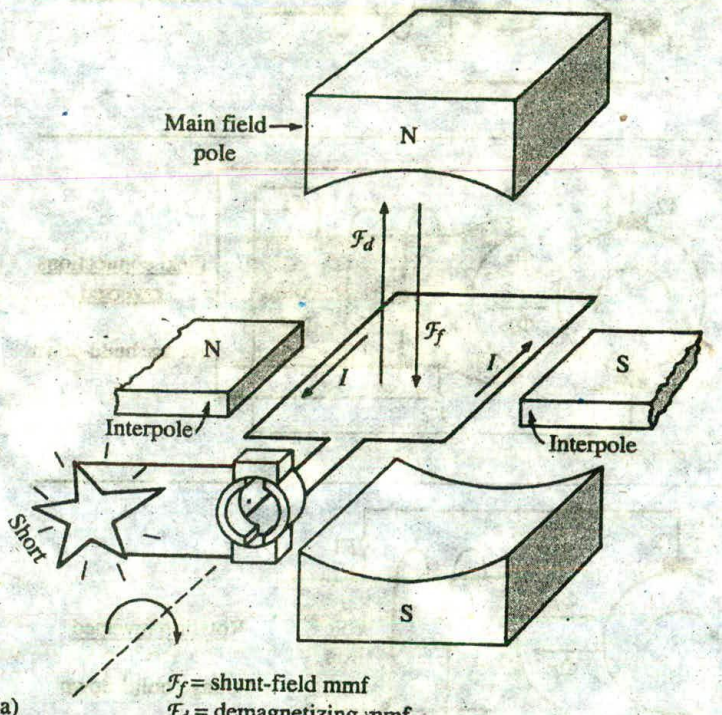


FIGURE 12.5
Factors affecting voltage buildup in a self-excited generator.

longer proportional to the armature current). The resultant high current in the commutated coil produces a strong demagnetizing mmf, shown as $\mathcal{F}_d$ in Figure 12.6(a). For simplicity, the shunt field windings and interpole windings are not shown. The direction of current in the commutated coil is determined by the direction of rotation and the polarity of the main field poles it left behind.



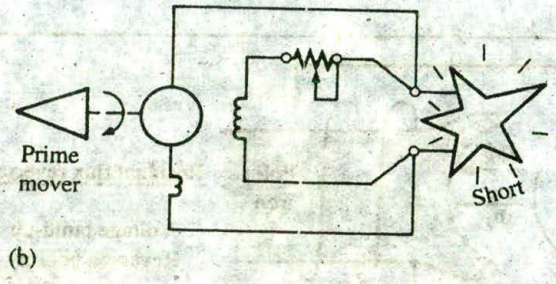


FIGURE 12.6
Effect of a short circuit on the polarity of a self-excited generator: (a) direction of component mmfs; (b) short circuiting the output terminals also short circuits the shunt field circuit.

Furthermore, referring to Figure 12.6(b), short circuiting the generator also short circuits the shunt field winding. This results in a very low shunt field current, and hence a very weak shunt field mmf. The combination of a weak shunt field mmf and a relatively high opposing mmf produced by the commutated coil reverses the residual magnetism in the main-pole iron. Thus, after the circuit breaker trips, the generator voltage will build up in the reverse direction.

12.6 LOAD-VOLTAGE CHARACTERISTICS OF SELF-EXCITED SHUNT GENERATORS

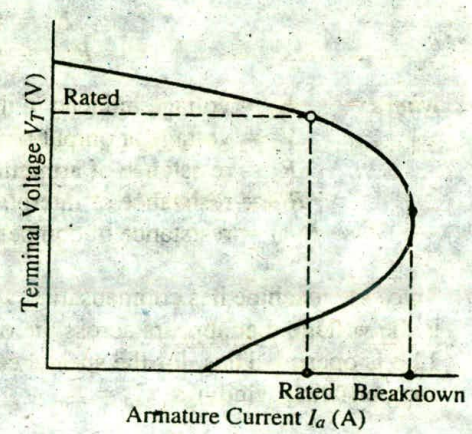
The behavior of self-excited shunt generators under various load conditions is more complex than that of separately excited machines. This is so because the field current of self-excited machines is dependent on the output voltage of the generator. The addition of load to a self-excited generator causes an IR drop in the armature circuit and a demagnetizing mmf due to armature reaction in uncompensated machines, both of which cause a lowering of the output voltage. The lowered output voltage reduces the shunt field current, causing a further reduction in voltage.

The dependency of field current on the output voltage, coupled with the nonlinearity of the magnetization curve, makes it necessary to use graphical techniques to determine the terminal voltage for a given load current. Such techniques are described and illustrated in References [2],[4].

Voltage Breakdown

The drop in output voltage due to a very heavy overload reduces the field current. This causes a further reduction in voltage and a rapid breakdown to almost zero volts, as shown in Figure 12.7. Should this occur, the generator circuit breaker must be tripped in order to rebuild voltage.

FIGURE 12.7
Load-voltage characteristic of a shunt generator that is loaded past the breakdown point.



12.7 GRAPHICAL APPROXIMATION OF THE NO-LOAD VOLTAGE

As previously discussed in Chapter 10, the voltage regulation of a DC generator is the percent change in terminal voltage from no load to rated load, with respect to rated voltage.

$$\text{VR} = \frac{V_{\text{nl}} - V_{\text{rated}}}{V_{\text{rated}}} \times 100 \quad \text{percent} \qquad \textbf{(10–16)}$$

where: VR = voltage regulation
V_{nl} = no-load (open-circuit) voltage (V)
V_{rated} = voltage indicated on nameplate of machine (V)

The no-load voltage may be obtained by operating the machine at its nameplate conditions, then removing the load and observing the no-load voltage. Although this is an exact method, it is not practical for very large machines.

An analytical method that provides a good approximation of the no-load voltage may be determined from the machine parameters and the associated magnetization curve. The magnetization curve must be used to account for magnetic saturation, the demagnetizing effect of armature reaction in noncompensated machines, and the effect of the series field mmf if the machine is a compound generator.

Separately Excited Shunt Generator With a Compensating Winding

Figure 12.8 shows a separately excited shunt generator, equipped with interpoles and a compensating winding. The machine is supplying rated load at the rated conditions specified on the generator nameplate.

Applying Kirchhoff's voltage law to the armature circuit,

$$E_a = V_T + I_a R_{\text{acir}} \qquad \textbf{(12–3)}$$
$$R_{\text{acir}} = R_a + R_{\text{IP}} + R_{\text{CW}}$$

where: E_a = voltage induced in the armature (V)
V_T = voltage at output terminals, load switch closed (V)
R_a = resistance of armature winding (Ω)
R_{IP} = resistance of interpole winding (Ω)
R_{CW} = resistance of compensating winding (Ω)

Since the machine has compensating windings, armature reaction is eliminated and E_a is the voltage that appears across the output terminals when the load switch in Figure 12.8 is opened. Thus, for the special case of a separately excited shunt generator with compensating windings, $V_{\text{nl}} = E_a$.

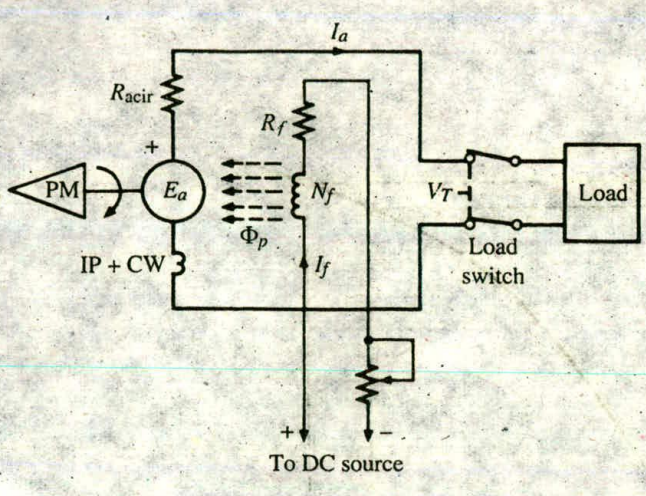


FIGURE 12.8
Separately excited shunt generator equipped with interpoles and a compensating winding.

Separately Excited Shunt Generator Without a Compensating Winding

If the generator in Figure 12.8 is designed without compensating windings, then

$$E_a = V_T + I_a(R_a + R_{IP}) \qquad \textbf{(12–4)}$$

Equation (12–4) does not account for armature reaction nor the effect of magnetic saturation. The effect of armature reaction on the induced emf is shown on the magnetization curve in Figure 12.9. With the load switch open, the armature current is zero and voltage V_{ni} is due to the field mmf ($\mathcal{F}_f$) alone. With the load switch closed, the demagnetizing effect of armature reaction, shown as an equivalent demagnetizing mmf ($\mathcal{F}_d$) in Figure 12.9, causes a net reduction in flux:

$$\mathcal{F}_{net} = \mathcal{F}_f - \mathcal{F}_d$$

This results in a lowered induced emf E_a.

EXAMPLE 12.2 A 300-kW, 240-V, 900 r/min, separately excited, noncompensated shunt generator has the following parameters: $R_a = 0.00234\ \Omega$, $R_{IP} = 0.00080\ \Omega$, and $R_f = 18.1\ \Omega$. The shunt field has 1020 turns/pole, and is separately excited from a 120-V source through a rheostat. The circuit diagram and magnetization curve for the generator are shown in Figure 12.10. The equivalent demagnetizing ampere-turns caused by armature

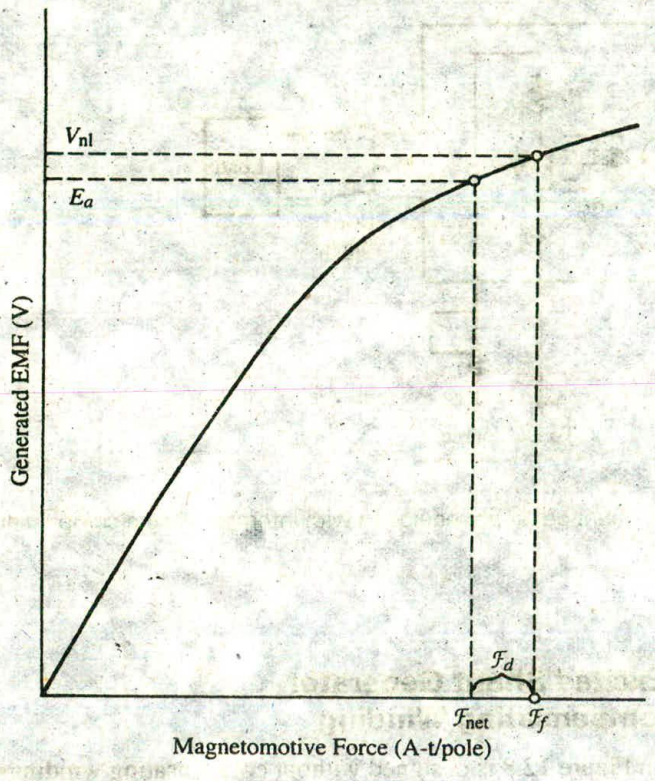


FIGURE 12.9
Magnetization curves showing the effect of armature reaction on the induced emf.

reaction, when supplying rated load at rated voltage and rated temperature, is assumed equal to 12.1 percent of the shunt field mmf. Determine (a) no-load voltage; (b) voltage regulation; (c) resistance setting of rheostat necessary to obtain rated voltage at rated conditions.

Solution

(a) $P = V_T I_a \quad \Rightarrow \quad 300{,}000 = 240 \times I_a \quad \Rightarrow \quad I_a = \underline{1250 \text{ A}}$

$E_a = V_T + I_a(R_a + R_{IP}) = 240 + 1250(0.00234 + 0.00080)$

$E_a = 243.9 \text{ V}$

The net mmf that results in $E_a = 243.9$ V is determined from the magnetization curve in Figure 12.10 to be ≈5100 A-t/pole.

$$\mathcal{F}_{net} = \mathcal{F}_f - \mathcal{F}_d = \mathcal{F}_f(1 - 0.121)$$

$$\mathcal{F}_f = \frac{5100}{1 - 0.121} = 5802 \text{ A-t/pole}$$

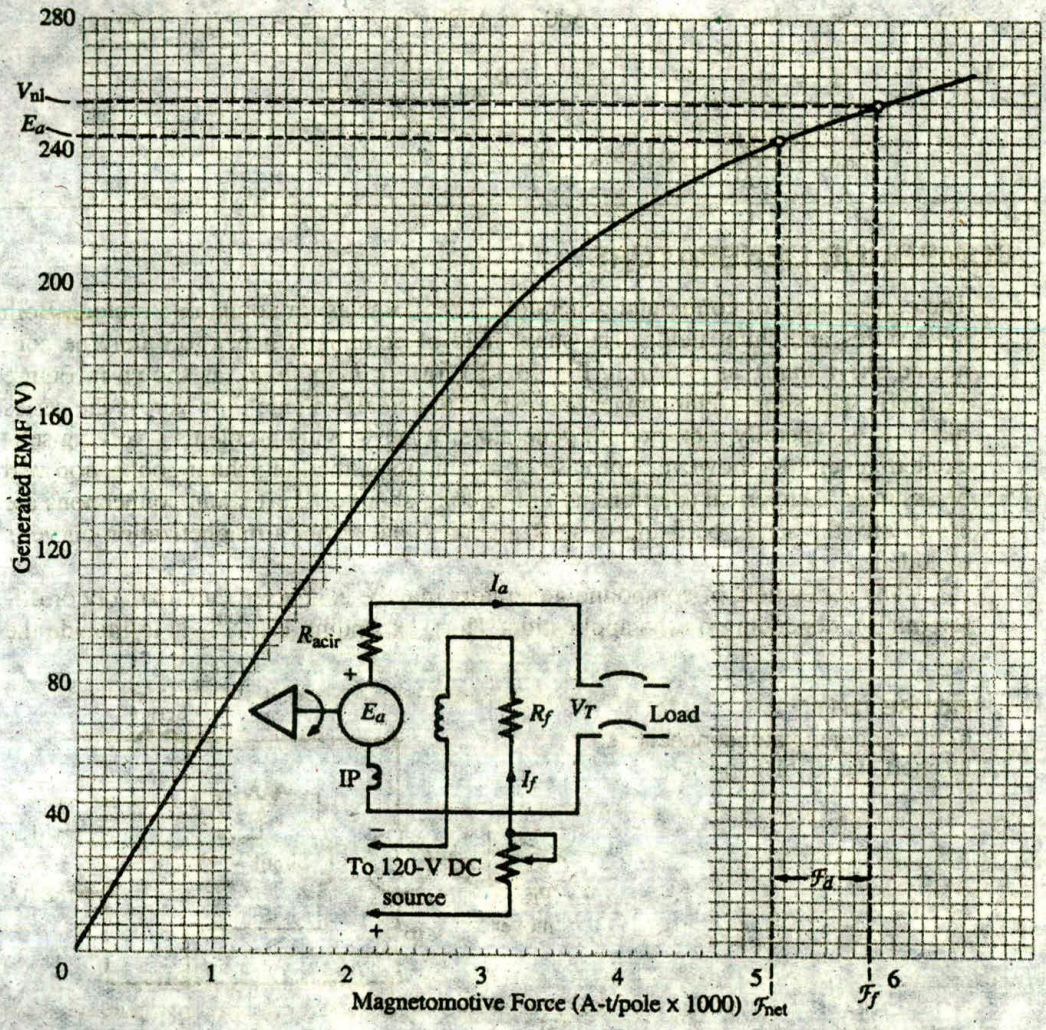


FIGURE 12.10
Magnetization curve and circuit diagram for Example 12.2.

The corresponding induced emf, as obtained from the magnetization curve in Figure 12.10, is the no-load voltage:

$$V_{nl} \approx \underline{255 \text{ V}}$$

(b) $$\text{VR} = \frac{V_{nl} - V_{rated}}{V_{rated}} \times 100 \quad \Rightarrow \quad \frac{255 - 240}{240} \times 100 = \underline{6.25\%}$$

(c) $\mathcal{F}_f = N_f I_f \quad \Rightarrow \quad 5802 = 1020 \times I_f \quad \Rightarrow \quad I_f = 5.69 \text{ A}$

$$I_f = \frac{V_f}{R_f + R_{\text{rheo}}} \quad \Rightarrow \quad R_{\text{rheo}} = \frac{V_f}{I_f} - R_f$$

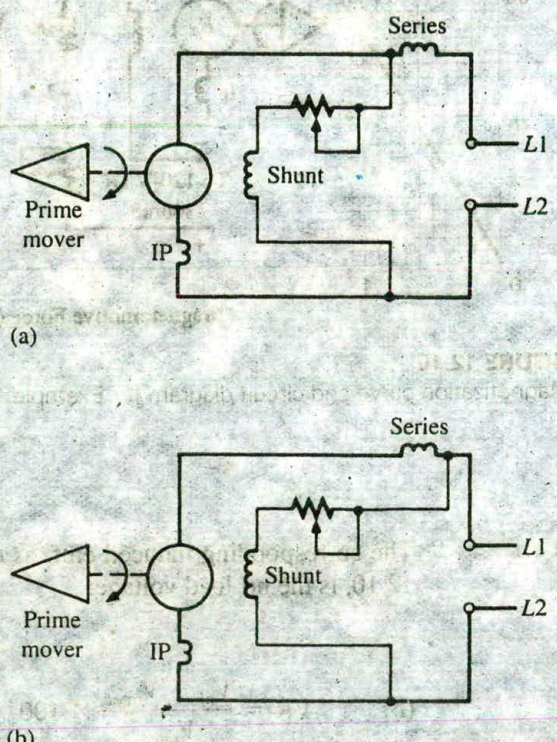
$$R_{\text{rheo}} = \frac{120}{5.69} - 18.1 = \underline{3.0\ \Omega}$$

12.8 COMPOUND GENERATORS

The construction of compound generators is the same as for compound motors: Both have series and shunt fields. The shunt field of compound generators may be connected *short shunt*, as shown in Figure 12.11(a), or *long shunt*, as shown in Figure 12.11(b). The short-shunt connection avoids the small voltage drop across the series field and is generally preferred for generators. When solving problems involving self-excited generators, however, for ease of calculations, the long-shunt connection will be assumed. Numerical solutions assuming long-shunt or short-shunt connections are essentially the same, particularly so if graphical data from a magnetization curve is included.

The series field of compound generators may be connected cumulatively or differentially, depending on the application. Thus, expanding Eq. (12–1) to include the

FIGURE 12.11
Compound generator connections: (a) short shunt; (b) long shunt.



series field mmf (assuming cumulative compounding) and the equivalent demagnetizing mmf due to armature reaction,

$$E_a = n \cdot \left[\frac{\mathcal{F}_f + \mathcal{F}_s - \mathcal{F}_d}{\mathcal{R}} \right] k_G \qquad \textbf{(12–5)}$$

where: $\mathcal{F}_f$ = shunt field mmf ($N_f I_f$) (A-t/pole)
$\mathcal{F}_s$ = series-field mmf ($N_s I_a$) (A-t/pole)
$\mathcal{F}_d$ = equivalent demagnetizing mmf due to armature reaction (A-t/pole)

Note: Although not exact, $\mathcal{F}_d$ is assumed proportional to the armature current. If a compensating winding is used, however, $\mathcal{F}_d = 0$. Thus, as indicated in Eq. (12–5), for a given armature current the increase in induced emf caused by the series field is dependent on the amount of compounding. More turns in the series field will produce higher emfs with the same load current. If enough turns are added to compensate for voltage drops caused by armature-circuit resistance and armature reaction, the terminal voltage will be essentially the same at no load as at full load, and the machine is said to be *flat compounded.* More than the minimum number of turns required for a flat-compound machine will cause the terminal voltage to rise with increasing load current; the machine is then said to be *overcompounded.* Less than the minimum number of turns will result in an *undercompound* machine. If the series field is differentially connected, its mmf will be negative, and an increase in the armature current will cause a decrease in flux and a corresponding decrease in generated emf. Figure 12.12 illustrates the variation in voltage from no load to full load for different types of compounding.

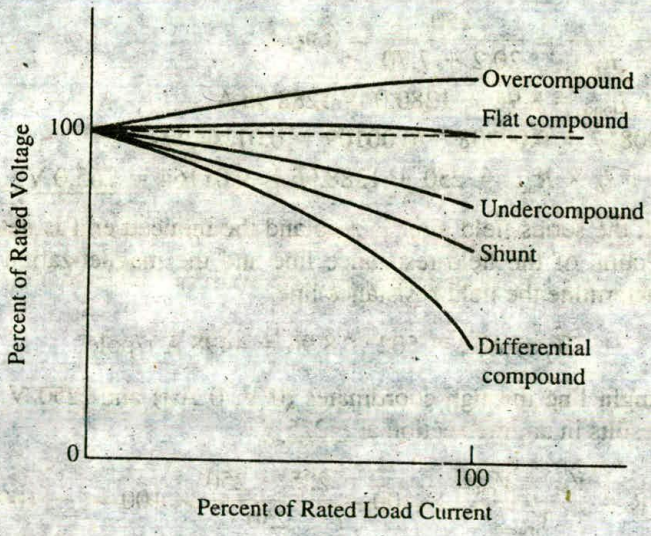


FIGURE 12.12
Comparison of load-voltage characteristics for different degrees of compounding.

Overcompound machines are used when DC power is to be transmitted over long distances; the rise in terminal voltage with load compensates for the voltage drop in the transmission line. A flat-compound machine is used when an essentially unvarying voltage is required and the distance of transmission is short. Shunt and undercompound generators are more stable for parallel operation than are flat and overcompound machines.

Differential compound generators are used when inherent overload protection is more desirable than a fixed voltage. Examples of its application are in generators supplying electric winches, and dredges, where an overload or short circuit would cause sufficient voltage drop to limit the current to a safe value.

EXAMPLE 12.3 A 250-V, 320-kW, 1150 r/min, self-excited, cumulative-compound, long-shunt generator is operating at rated conditions with the shunt field rheostat set for 7.70 Ω. The shunt field has 502 turns/pole, the series field has 1 turn/pole, and the generator parameters, expressed in ohms, are

Armature	IP + CW	Series	Shunt
0.00817	0.00238	0.00109	20.2

The circuit diagram and magnetization curve are shown in Figure 12.13. Determine (a) induced emf at rated load; (b) no-load voltage; (c) voltage regulation. (d) What is the type of compounding?

Solution

(a) $P_{load} = V_T I_{load} \quad \Rightarrow \quad 320{,}000 = 250 \times I_{load} \quad \Rightarrow \quad I_{load} = 1280.0 \text{ A}$

$$I_f = \frac{V_T}{R_f + R_{rheo}} = \frac{250}{20.2 + 7.70} = 8.96 \text{ A}$$

$$I_a = I_f + I_{load} = 8.96 + 1280.0 = 1288.96 \text{ A}$$

$$R_{acir} = 0.00817 + 0.00238 + 0.00109 = 0.01164 \ \Omega$$

$$E_a = V_T + I_a \times R_{acir} = 250 + 1288.96 \times 0.01164 = \underline{265.0 \text{ V}}$$

(b) At no load, the series-field mmf is zero and the induced emf is determined from the intersection of the field-resistance line and the magnetization curve. Using 250 V to determine the field-resistance line,

$$\mathcal{F}_f = N_f I_f = 502 \times 8.96 = 4498 \text{ A-t/pole}$$

Drawing a straight line through coordinates (0 V, 0 A-t) and (250 V, 4498 A-t) in Figure 12.13 results in an intersection at $\underline{\approx 225 \text{ V}}$.

(c)
$$\text{VR} = \frac{V_{nl} - V_{rated}}{V_{rated}} \times 100 = \frac{225 - 250}{250} \times 100 = \underline{-10\%}$$

(d) The machine is overcompounded.

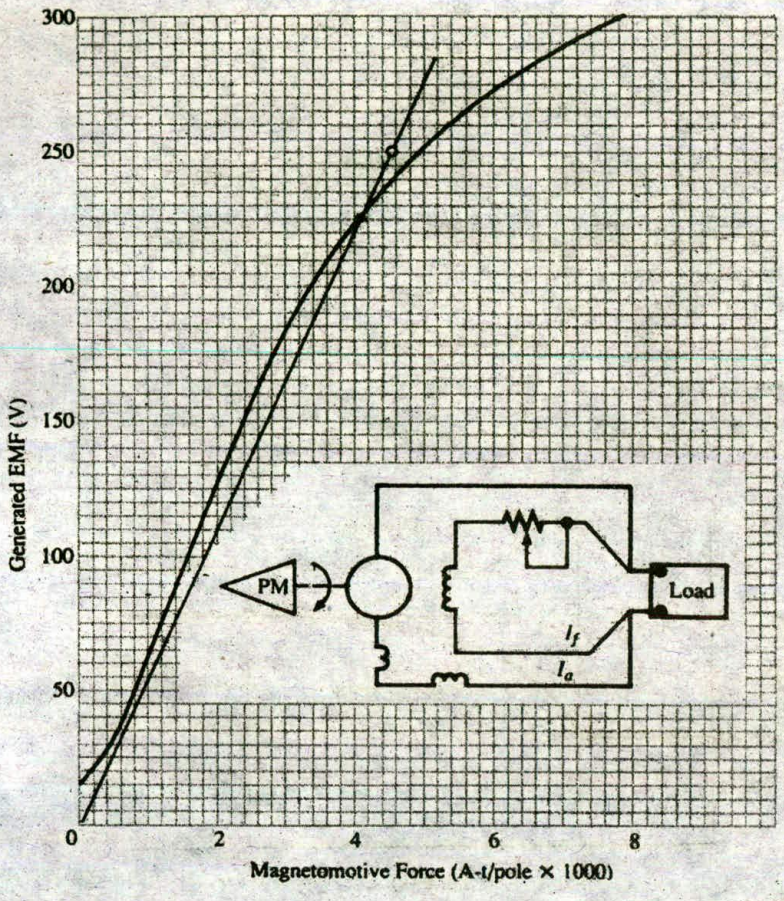
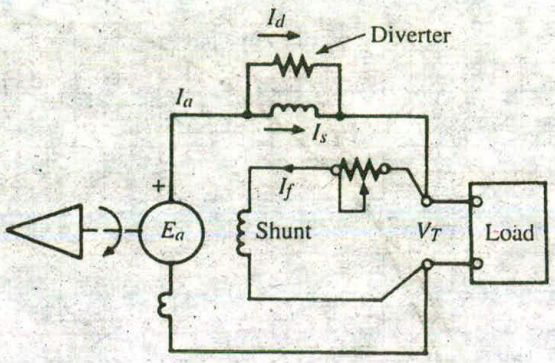


FIGURE 12.13
Magnetization curve and circuit diagram for Example 12.3.

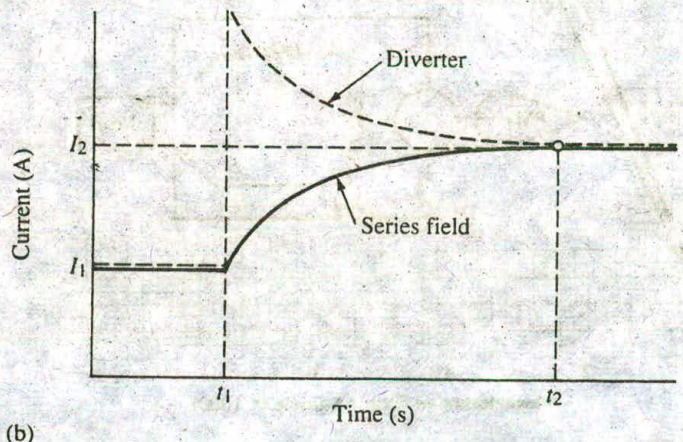
12.9 SERIES-FIELD DIVERTER

The compounding of a generator may be reduced by diverting some of the armature current that would normally be in the series-field coils. This is illustrated in Figure 12.14(a), where a resistor, called a *diverter* or *series-field shunt,* is shown connected in parallel with the series field winding. The diverter is constructed of nichrome or other resistance material and mounted outside the generator housing.

The application of series-field diverters to generators that are subject to sudden heavy-load swings, however, requires that the diverter be made inductive by winding it on a laminated iron core. The reason for this is illustrated in Figure 12.14(b), assuming a noninductive diverter whose resistance is equal to the resistance of the series field. The noninductive diverter responds more rapidly to *changes in load current* than



(a)



(b)

FIGURE 12.14
(a) Compound generator with a series-field diverter; (b) current transients in the series field and in the noninductive diverter for a suddenly applied load.

does the series field. Thus, as shown in Figure 12.14(b), the application of a sudden heavy load at time t_1 results in a delay in the buildup of current through the series field, and hence a delay in the buildup of generator emf. For optimum performance, diverters for compound generators with rapidly fluctuating loads should be designed to have the same inductive time constant as that of the series field.

EXAMPLE 12.4 The series field winding of a 170-kW, 250-V, 1450 r/min compound generator has a resistance of 0.00306 Ω. Determine (a) required resistance of a noninductive diverter that will bypass 27 percent of the total armature current; (b) power rating of the diverter.

Solution

The circuit is similar to that shown in Figure 12.14(a).

(a) $I_s = 0.73I_a \qquad I_d = 0.27I_a$

Since the voltage drop across the diverter is the same as that across the series-field winding,

$$I_sR_s = I_dR_d \quad \Rightarrow \quad R_d = R_s \cdot \frac{I_s}{I_d} = 0.00306 \times \frac{0.73}{0.27} = \underline{0.00827\ \Omega}$$

(b) $$I_a = \frac{P_{\text{load}}}{V_T} = \frac{170{,}000}{250} = 680\ \text{A}$$

$$P_d = I_d^2R_d = (680 \times 0.27)^2 \times 0.00827 = \underline{279\ \text{W}}$$

12.10 COMPOUNDING EFFECT OF SPEED

The speed of a generator has a pronounced effect on the degree of compounding. When operating at higher speeds, the flux contributed by the series field will be more effective in generating an emf. Although the shunt field rheostat can be adjusted to provide the same output voltage at different speeds, the series-field mmf is a function of the load current and cannot be adjusted by rheostat action. Hence, when operating above rated speed, a flat compound generator will behave like an overcompound machine, and when operating below rated speed it will behave like an undercompound machine.

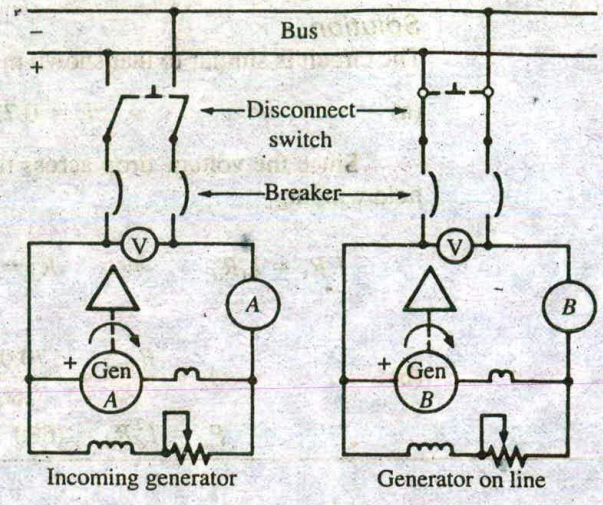
12.11 PARALLELING DIRECT-CURRENT GENERATORS

When the load demanded from a system of generators exceeds the amount that can be safely supplied, additional generators must be switched onto the system to carry the additional load. Referring to Figure 12.15, GEN *B* is connected to the bus, and GEN *A* (the incoming machine) is about to be paralleled with GEN *B*. The disconnect switch permits isolation of the circuit breaker from the bus for purposes of test, maintenance, and repair.

Procedure for Paralleling

1. Close the generator disconnect switch of the incoming machine.
2. Start the prime mover and adjust it to rated speed.
3. Adjust the voltage of the incoming machine to be a few volts higher than the bus voltage.
4. Close the generator breaker.

FIGURE 12.15
Circuit diagram showing connections for parallel operation of DC generators.



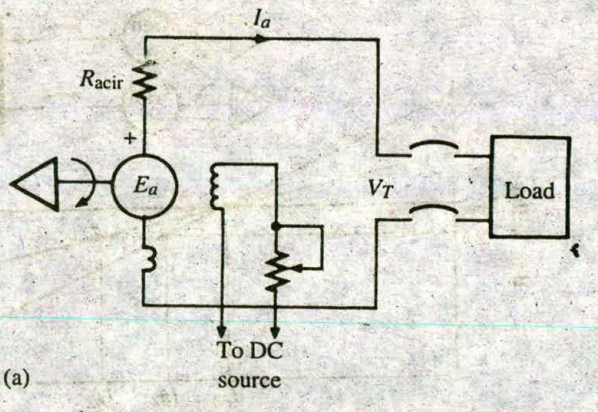
5. Turn the shunt field rheostat of the incoming machine in the "raise voltage" direction, and that of the other machine or machines on the bus in the "lower voltage" direction until the desired load distribution is attained. Load distribution is indicated on the respective ammeters; wattmeters are not used.

Before attempting to parallel a newly installed machine or one that had been disconnected for repairs, a polarity check should be made to ensure that the positive terminal of the incoming machine will connect to the positive terminal of the bus. A simple polarity check may be made with a DC voltmeter, testing across the top terminals of the circuit breaker and then across the bottom terminals; corresponding terminals must have the same polarity. Paralleling a machine with reversed polarity effectively short circuits the generator and results in damaged brushes, a damaged commutator, and a blacked-out plant. Generators that have been tripped off the bus because of a heavy *fault current* (short circuit) should be checked for reversed polarity before reclosing the breaker.

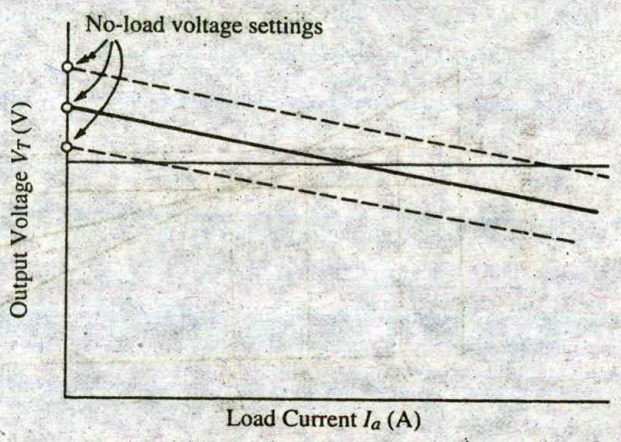
12.12 EFFECT OF FIELD-RHEOSTAT ADJUSTMENT ON THE LOAD-VOLTAGE CHARACTERISTICS OF DC GENERATORS

The circuit diagram and typical load-voltage characteristic of output voltage vs. armature current for a DC generator are shown in Figure 12.16. Although usually drawn as a straight line, the actual characteristic has a slight curve. The drooping characteristic provides inherent stability of operation when paralleled with other machines. Adjusting the shunt field rheostat raises or lowers the no-load voltage setting of the generator, but does not change the droop. Curves for different no-load voltage settings are shown with broken lines in Figure 12.16(b). For a given no-load voltage setting of the shunt field rheostat, a DC generator with a drooping characteristic can have only one value of load current for a given output voltage.

FIGURE 12.16
Circuit diagram and typical load-voltage characteristic of a DC generator, showing different no-load voltage settings.



(a)



(b)

12.13 DIVISION OF ONCOMING BUS-LOAD BETWEEN DC GENERATORS IN PARALLEL

The division of oncoming bus load between DC generators in parallel is determined by the voltage droop of the respective generators, which cannot be easily changed by the operator. This is shown in Figure 12.17(a), where two generators with different voltage droops are in parallel and supply equal shares of the total load current (subscript 1 on the curves).[2] The droop characteristics are exaggerated to illustrate the behavior of the machines as the bus load is increased or decreased. An increase in bus load causes an increase in the internal voltage drops, and thus a decrease in the bus voltage, shown with a broken line and subscript 2. Note that the generator with the least droop took a greater share of the *increase* in bus load.

[2]The one-line diagram in Figure 12.17(a) is an elementary representation of two generators connected to the bus.

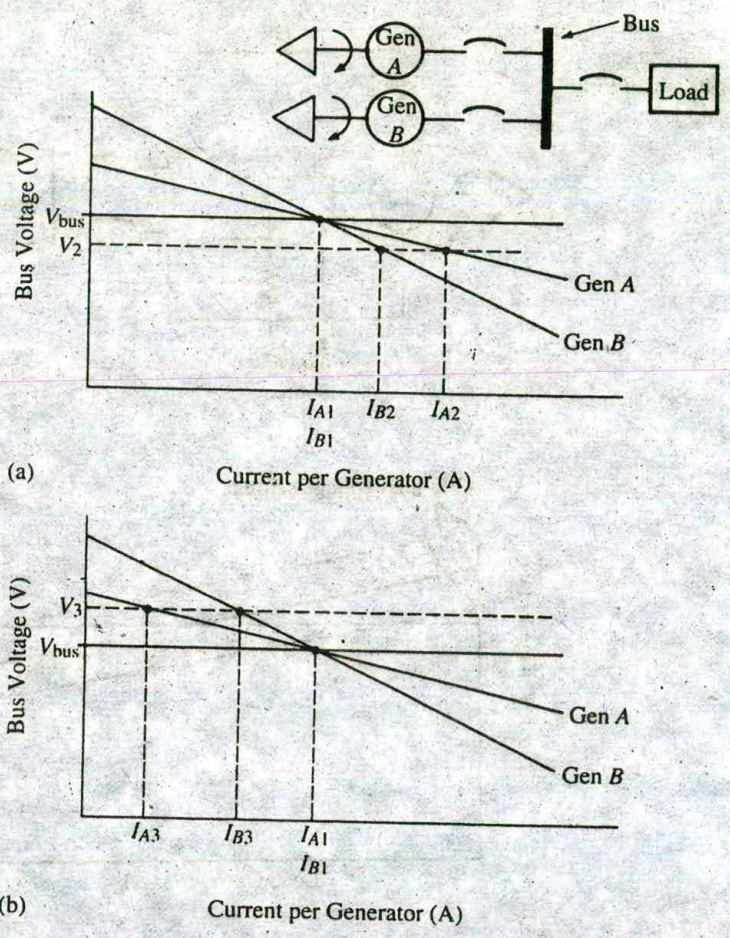


FIGURE 12.17
Load-voltage characteristics of two generators, with different voltage regulations, operating in parallel: (a) increasing bus load; (b) decreasing bus load.

Similarly, as shown in Figure 12.17(b), a decrease in bus load causes a decrease in the internal voltage drops and thus an increase in the bus voltage. As shown by subscript 3, the generator with the least droop assumed a greater share of the *change* in bus load. Whether the bus load is increasing or decreasing, *the machine with the least droop always assumes a greater portion of the change in bus load.*

For optimum performance, machines operating in parallel should have the same voltage regulation, and for stability of operation, the voltage regulation should be between 3 and 8 percent, obtained by governor adjustment and/or electrical design. *Paralleled machines with different power ratings but the same voltage regulation will divide any oncoming bus load in direct proportion to their respective power ratings.*

12.14 CHARACTERISTIC TRIANGLE AS A TOOL FOR SOLVING LOAD-DISTRIBUTION PROBLEMS BETWEEN PARALLELED DC GENERATORS

The solution of problems involving load distribution between DC generators in parallel may be accomplished in a straightforward manner by defining a *characteristic triangle* for each machine, and then using similar triangles to determine a sclution.

Referring to Figure 12.18, the characteristic triangle is fixed for a given voltage droop and does not change with changes in the field-rheostat setting. The bus voltage is the terminal voltage (also called output voltage) of the generator.

An increase in bus load causes a decrease in bus voltage, as shown by the broken line in Figure 12.18. The intersection of the new voltage line with the load-voltage characteristic establishes a new triangle similar to the characteristic triangle. From the geometry of similar triangles,

$$\frac{\Delta V_{\text{bus}}}{\Delta I} = \frac{V_{\text{nl}} - V_{\text{rated}}}{I_{\text{rated}}} \tag{12–6}$$

From the voltage-regulation equation, Eq. (10–16),

$$V_{\text{nl}} - V_{\text{rated}} = \frac{\text{VR}}{100} \times V_{\text{rated}} \tag{12–7}$$

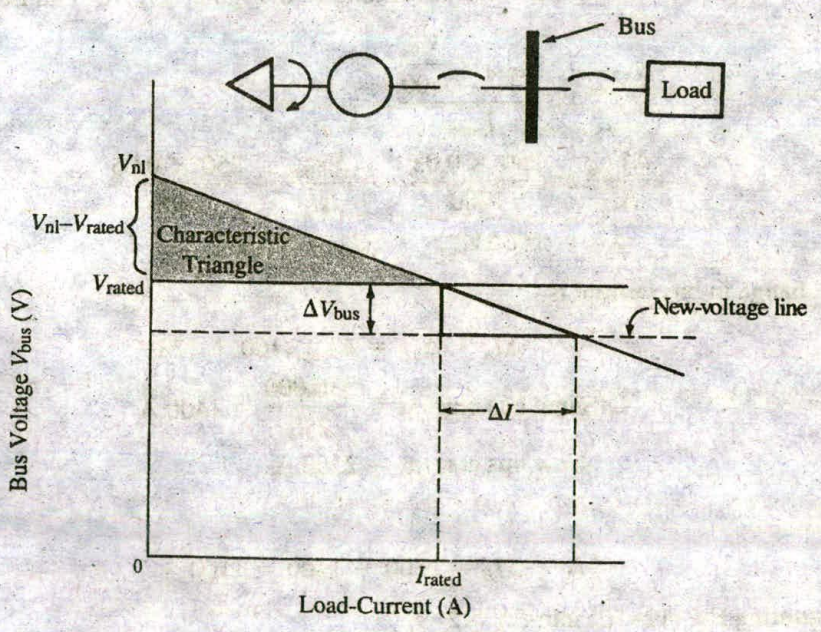


FIGURE 12.18
Characteristic triangle defines the droop characteristic of a generator.

Substituting Eq. (12–7) into Eq. (12–6),

$$\frac{\Delta V_{\text{bus}}}{\Delta I} = \frac{V_{\text{rated}} \times \dfrac{\text{VR}}{100}}{I_{\text{rated}}} \tag{12–8}$$

where: VR = voltage regulation
ΔI = change in generator load current (A)
ΔV_{bus} = change in bus voltage due to change in generator load current (V)

EXAMPLE 12.5 A 300-kW, 250-V DC generator *A* with a voltage regulation of 3.0 percent, and a 400-kW, 250-V DC generator *B*, with a voltage regulation of 5.0 percent, are operating in parallel and taking equal shares of a 350-kW, 250-V bus load. A one-line diagram of the paralleled machines is shown in Figure 12.19(a). If the bus load is increased to 2500 A, determine (a) new bus voltage; (b) current supplied by each generator.

Solution

(a) Neglecting the relatively small shunt field current,

$$I_{A,\text{rated}} = \frac{300{,}000}{250} = 1200 \text{ A} \qquad I_{B,\text{rated}} = \frac{400{,}000}{250} = 1600 \text{ A}$$

Substituting data from the characteristic triangles in Figure 12.19(b) into Eq. (12–8),

$$\frac{\Delta V_{\text{bus}}}{\Delta I} = \frac{V_{\text{rated}} \times \dfrac{\text{VR}}{100}}{I_{\text{rated}}}$$

$$\frac{\Delta V_{\text{bus}}}{\Delta I_A} = \frac{250 \times 0.03}{1200} \qquad \frac{\Delta V_{\text{bus}}}{\Delta I_B} = \frac{250 \times 0.05}{1600}$$

$$\Delta I_A = 160 \Delta V_{\text{bus}} \qquad \Delta I_B = 128 \Delta V_{\text{bus}}$$

The change in bus current is

$$\Delta I_A + \Delta I_B = \Delta V_{\text{bus}}(160 + 128) \tag{12–9}$$

$$\text{Original bus current} = \frac{350{,}000}{250} = 1400 \text{ A}$$

$$\text{New bus current} = 2500 \text{ A}$$

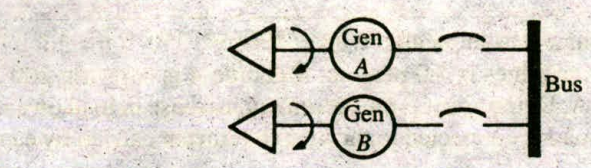
Thus,

$$\Delta I_A + \Delta I_B = 2500 - 1400 = 1100 \text{ A} \tag{12–10}$$

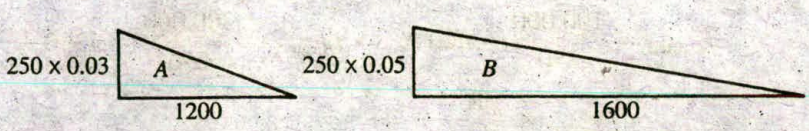
Substituting Eq. (12–10) into Eq. (12–9),

$$1100 = \Delta V_{\text{bus}} \times (160 + 128)$$

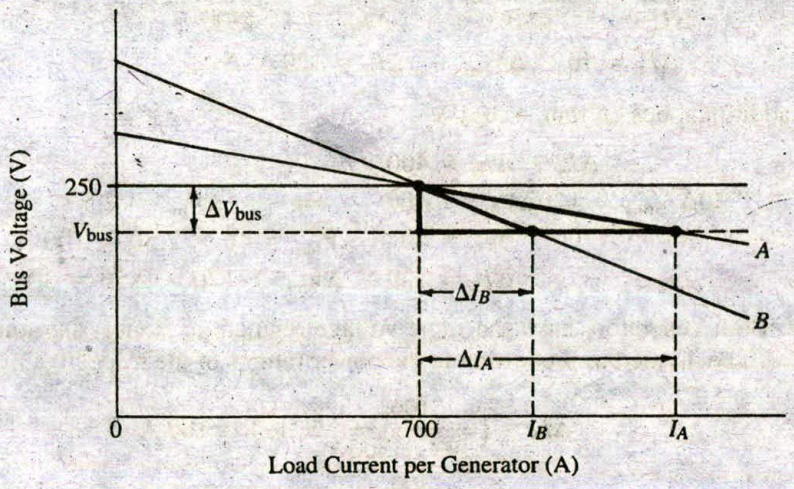
$$\Delta V_{\text{bus}} = 3.82 \text{ V}$$



(a)



(b)



(c)

FIGURE 12.19
Illustrations for Example 12.5: (a) one-line diagram; (b) characteristic triangles; (c) load-voltage characteristics.

From Figure 12.19(c),

(b)
$$V_{bus} = 250 - \Delta V_{bus} = 250 - 3.82 = \underline{246.18 \text{ V}}$$
$$I_A = 700 + \Delta I_A = 700 + \underline{160} \times 3.82 = \underline{1311 \text{ A}}$$
$$I_B = 700 + \Delta I_B = 700 + 128 \times 3.82 = \underline{1189 \text{ A}}$$

Note: Machine *A* is overloaded by

$$\frac{1311 - 1200}{1200} \times 100 = 9.2\%$$

EXAMPLE 12.6 A 100-kW, 250-V machine *A* is in parallel with a 300-kW, 250-V machine *B*. The voltage regulation of both machines is 4.0 percent. Machine *A* is carrying 200 A, and machine *B* is carrying 500 A. Determine (a) the increment increase in load on each machine if an additional 400-A load is connected to the bus; (b) current carried by each machine.

Solution

(a) Using the methods illustrated in Example 12.5,

$$I_{A,\text{rated}} = \frac{100{,}000}{250} = 400 \text{ A} \qquad I_{B,\text{rated}} = \frac{300{,}000}{250} = 1200 \text{ A}$$

$$\frac{\Delta V_{\text{bus}}}{\Delta I} = \frac{V_{\text{rated}} \times \dfrac{\text{VR}}{100}}{I_{\text{rated}}}$$

$$\frac{\Delta V_{\text{bus}}}{\Delta I_A} = \frac{250 \times 0.04}{400} \qquad \frac{\Delta V_{\text{bus}}}{\Delta I_B} = \frac{250 \times 0.04}{1200}$$

$$\Delta I_A = 40 \times \Delta V_{\text{bus}} \qquad \Delta I_B = 120 \times \Delta V_{\text{bus}}$$

The additional bus current = 400 A

$$\Delta I_A + \Delta I_B = 400$$

$$40\Delta V_{\text{bus}} + 120\Delta V_{\text{bus}} = 400 \quad \Rightarrow \quad \Delta V_{\text{bus}} = 2.5 \text{ V}$$

$$\Delta I_A = 40 \times \Delta V_{\text{bus}} = 40 \times 2.50 = \underline{100 \text{ A}}$$

$$\Delta I_B = 120 \times \Delta V_{\text{bus}} = 120 \times 2.50 = \underline{300 \text{ A}}$$

Note: Both generators have the same voltage regulation. Hence, any oncoming bus load will be divided in proportion to the power ratings of the respective machines.

$$\Delta I_A = \left(\frac{100}{100 + 300}\right) \times 400 = 100 \text{ A}$$

$$\Delta I_B = \left(\frac{300}{100 + 300}\right) \times 400 = 300 \text{ A}$$

A much easier solution!

(b)

$$I_A = 200 + 100 = \underline{300 \text{ A}}$$

$$I_B = 500 + 300 = \underline{800 \text{ A}}$$

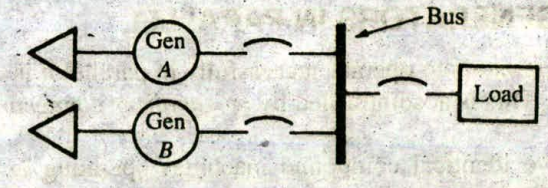
12.15 THEORY OF LOAD TRANSFER BETWEEN DC GENERATORS IN PARALLEL

The transfer of bus load between generators is easily accomplished by using the respective field rheostats to change the no-load voltage settings of the respective machines. The machine that is to take some load should have its field rheostat turned in the "raise voltage" direction, and the machine that is to lose some load should have its field rheostat turned in the "lower voltage" direction. Observations of load are made

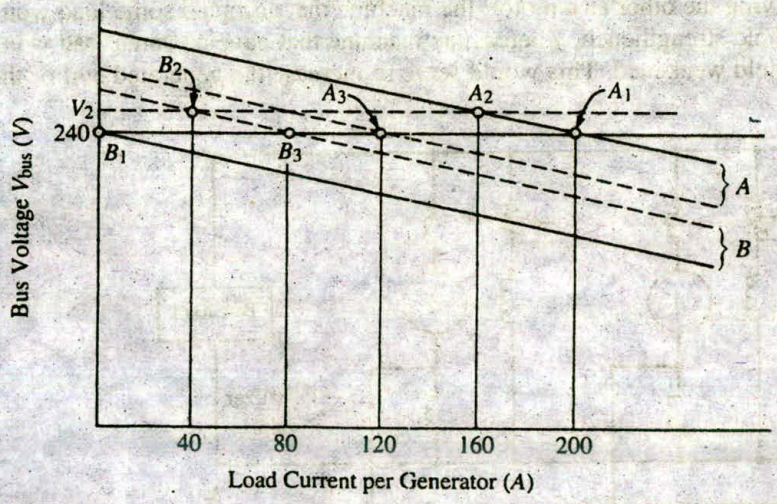
on the generator ammeters. Wattmeters are not required and are rarely used. The transfer of load may be made by simultaneous adjustment of both generator rheostats or by separate adjustment on each machine until the desired transfer is accomplished.

Although the transfer of load between DC generators is accomplished indirectly through the medium of field excitation, the energy supplied by each generator is still dependent on the energy input to its respective prime mover; the machine that had its excitation increased generates a higher emf, causing an increase in its current output. Assuming the bus load is constant (e.g., a fixed lighting load), the increased current output of one machine will result in a decrease in current output of the other machine. The machine that accepted the additional load starts to slow down and its speed governor reacts to admit more energy to its prime mover. The machine that lost some load starts to speed up, and its speed governor reacts to decrease the energy input to its prime mover.

Figure 12.20 illustrates a two-step procedure for the transfer of load between shunt machines with identical load-voltage characteristics. Machine *A* carries a load of 200 A at 240 V, and machine *B* has just been paralleled and is carrying no load. The initial conditions are indicated by subscript 1 and the use of solid lines. To transfer



(a)



(b)

FIGURE 12.20
One-line diagram and load-voltage characteristics illustrating load transfer through shunt field rheostat control.

load from machine *A* to machine *B* and still maintain 240 V requires adjustment of the field rheostats of both machines.

Assume that 80 A are to be transferred from machine *A* to machine *B*. For the example shown in Figure 12.20, the field current of machine *B* is increased by adjustment of its field rheostat until one-half the amount of load that is to be transferred is shifted—namely, 40 A. This adjustment raises the no-load voltage setting, and hence the entire characteristic of machine *B*. The bus will then operate at some higher voltage V_2, and the characteristic of machine *A* will intersect the new voltage line at 160 A, as denoted by subscript 2. To complete the transfer of load, the field rheostat of machine *A* is adjusted to decrease its excitation until the remaining 40 A are transferred. The characteristic of machine *A* is thereby lowered, and the voltage of the system comes back to its original 240-V value. This is indicated by subscript 3, where machine *A* takes 120 A and machine *B* takes 80 A. The slope of the curves was not changed throughout the transition period. The entire characteristic of each machine was moved either up or down by adjustment of the field rheostats.

12.16 COMPOUND GENERATORS IN PARALLEL

For compound generators to operate successfully in parallel it is necessary to parallel their series fields. This is accomplished by an *equalizer connection*, such as is shown in Figure 12.21.

Consider two identical compound machines operating in parallel without an equalizer, and with the bus load carefully balanced between the two. Any attempt to transfer some of the load from one machine to the other by adjustment of the field rheostats would result in the machine with the greater excitation taking the entire load and driving the other as a motor; the machine that accepted some load would have its series field strengthened, whereas the machine that gave up some load would have its series field weakened. This would serve to increase the generated emf of the machine

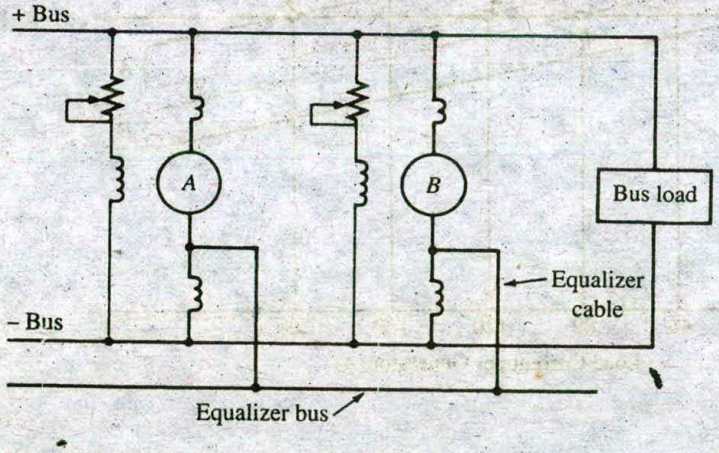


FIGURE 12.21
Compound generators in parallel, showing equalizer connections.

that accepted some load and to decrease the generated emf of the machine that gave up some load, resulting in an additional load transfer, etc.

Furthermore, motoring of a compound generator without an equalizer would result in a reversal of current through its series field, causing it to act as a differential compound motor. If the motoring generator is not immediately tripped off the bus, and the series field mmf is greater than the shunt field mmf, the polarity of the residual magnetism will be reversed; when the machine is restarted it will build up voltage in the reverse direction. When equalizers are used, however, accidental or deliberate motoring of a compound generator cannot cause reversed polarity.

The resistance of each equalizer cable (and its connections) should not exceed 20 percent of the resistance of the series field winding of the smallest of the paralleled machines [3]. This ensures that the series fields of paralleled generators will divide the total bus current in the approximate inverse ratio of their respective series-field resistances.

12.17 REVERSE-CURRENT TRIP

A reverse-current trip provides protection against sustained motoring. The layout and connections of one type of reverse-current trip are shown in Figure 12.22. The series coil is wound around an iron bar, called the armature, and connected in series with the

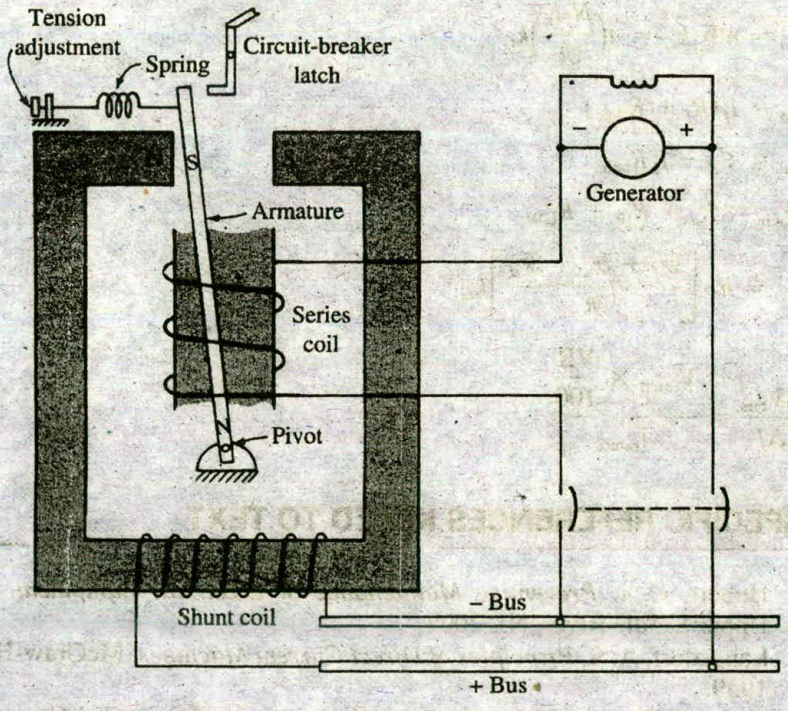


FIGURE 12.22
Reverse-current trip.

generator armature. The iron bar is pivoted at the bottom and free to move within the coil. Current in the series coil magnetizes the iron bar in the vertical direction. The shunt coil is connected across the bus and establishes the flux of the horseshoe magnet. The two coil connections are arranged so that as long as the generator current is in the proper direction the iron bar will be held in the nontripping position. If for some reason the generator voltage falls below that of the bus, however, the current in the generator will reverse its direction. This will reverse the polarity of the iron bar and cause it to be attracted by the opposite pole of the horseshoe magnet. Movement of the iron bar trips the circuit-breaker latch and the machine is tripped off the line. A spring with very light tension is used to hold the bar in the nontripping position. This is necessary to prevent vibration from accidentally tripping the circuit breaker when the generator is lightly loaded. The spring tension may be adjusted to vary the amount of reverse current required to operate the trip.

SUMMARY OF EQUATIONS FOR PROBLEM SOLVING

$$\text{VR} = \frac{V_{\text{nl}} - V_{\text{rated}}}{V_{\text{rated}}} \times 100 \text{ percent} \qquad \textbf{(10–16)}$$

$$E_a = n\Phi_p k_G = n\left(\frac{N_f I_f}{\mathcal{R}}\right)k_G \qquad \textbf{(12–1)}$$

$$E_a = I_f(R_f + R_{\text{rheo}}) \qquad \textbf{(12–2)}$$

$$E_a = V_T + I_a R_{\text{acir}} \qquad \textbf{(12–3)}$$

$$R_{\text{acir}} = R_a + R_{\text{IP}} + R_{\text{CW}}$$

$$E_a = n \cdot \left[\frac{\mathcal{F}_f + \mathcal{F}_s - \mathcal{F}_d}{\mathcal{R}}\right]k_G \qquad \textbf{(12–5)}$$

$$\frac{\Delta V_{\text{bus}}}{\Delta I} = \frac{V_{\text{rated}} \times \dfrac{\text{VR}}{100}}{I_{\text{rated}}} \qquad \textbf{(12–8)}$$

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3. National Electrical Manufacturers Association. *Motors and Generators.* Publication No. MG-1-1998, NEMA, Rosslyn VA, 1999.
4. Siskind, C. S. *Direct Current Machinery.* McGraw-Hill, New York, 1952.

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Kloeffler, R. G., R. M. Kerchner, and J. L. Brenneman. *Direct-Current Machinery.* Macmillan, New York, 1949.

REVIEW QUESTIONS

1. (a) Sketch the magnetization curve and the field-resistance line for a self-excited generator. (b) Explain how the generator builds up its emf and what determines the maximum voltage that the generator may attain.
2. How may the voltage of a self-excited generator be adjusted?
3. What effect does the speed of a self-excited generator have on the buildup of voltage? Explain.
4. What basic faults can prevent a self-excited generator from building up voltage?
5. How can reversed polarity of a self-excited generator be detected and corrected?
6. (a) What is the function of the series field in a compound generator? (b) Explain why it is connected in series with the armature.
7. What is a diverter? How is it connected, and under what conditions would it be used?
8. How does a differential-compound generator differ from a cumulative-compound generator? State an application for the differential-compound machine.
9. Explain why changes in speed change the degree of compounding of a compound generator.
10. State in detail the procedure for paralleling one DC generator with another that is already on the bus. Include in your statement the instruments observed and the equipment operated.
11. How can the transfer of load be accomplished between two DC generators in parallel? Include in your statement the equipment operated and the instruments observed.
12. Explain why adjustment of the field excitation of a DC generator causes a shift in load between machines in parallel.
13. Two DC generators with identical drooping load-voltage characteristics are operating in parallel. Each machine carries an equal share of the bus load at 500 V. Sketch on one set of coordinate axes the approximate load-voltage characteristics and draw the 500-V line. With broken lines appropriately drawn and lettered to indicate the transition steps, show and explain how a portion of the load of one machine can be transferred to the other machine, and still have the same bus voltage when the transfer is completed.
14. Explain how the equalizer stabilizes the operation of compound generators in parallel.
15. If two cumulative-compound generators are connected in parallel without an equalizer, any attempt to transfer some load from one to the other may result in the motoring of one of the machines. Explain this behavior.
16. Explain the operation of the reverse-current trip as used in a generator breaker.

PROBLEMS

12–1/7 A 150-kW, 250-V, 1750 r/min, separately excited, noncompensated shunt generator has the following parameters: $R_{acir} = 0.0072\ \Omega$, $R_f = 18.6\ \Omega$, $N_f = 1491$ turns/pole. The field is excited from a 120-V source, and the magnetization curve is shown in Figure 12.23. The machine is operating at rated load, and the equivalent demagnetizing mmf caused by armature reaction is 15.2 percent of the shunt field mmf. Determine (a) no-load voltage;

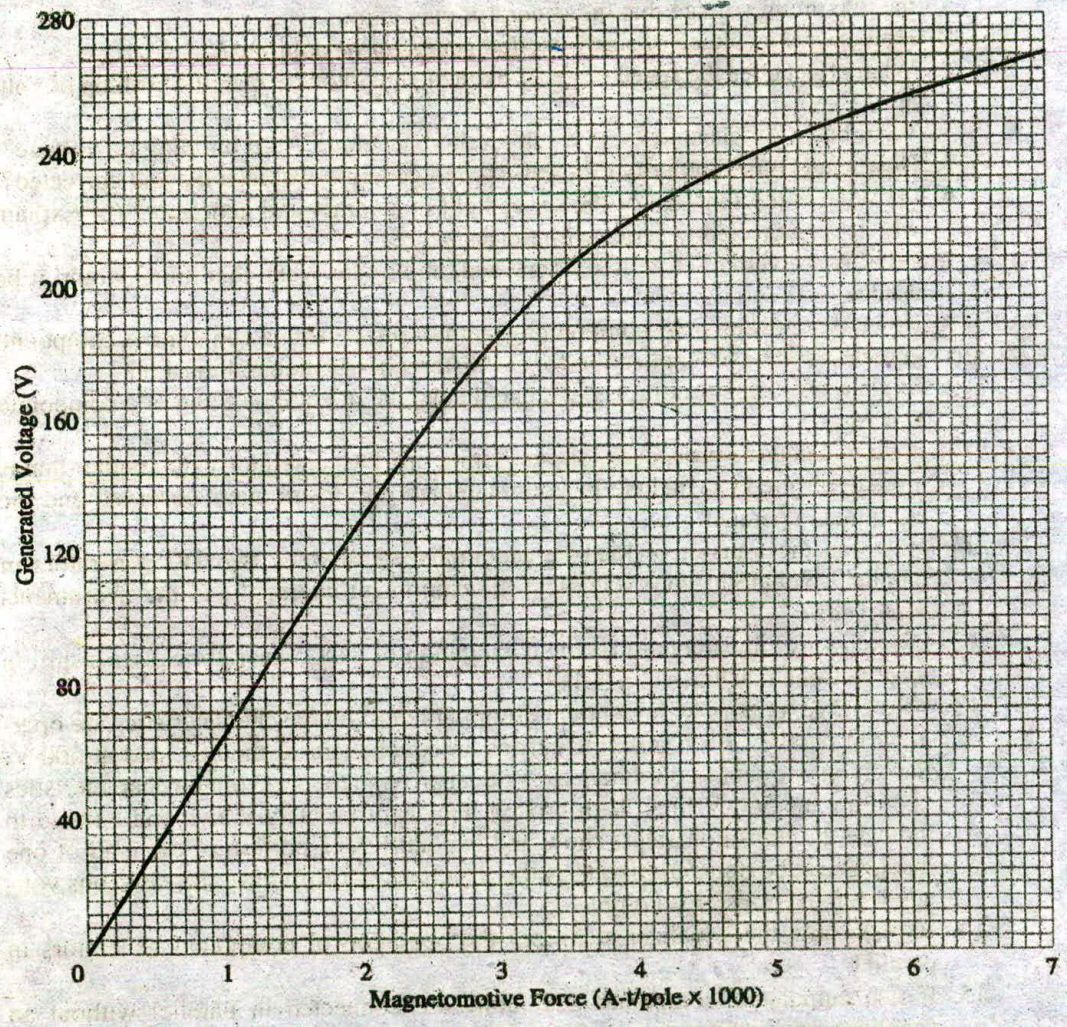


FIGURE 12.23
Magnetization curve for Problems 12–1/8 through 12–3/8.

(b) voltage regulation; (c) resistance of rheostat setting necessary to obtain rated voltage at rated conditions.

12–2/7 A 100-kW, 1750 r/min, 240-V, separately excited shunt generator without compensating windings has the following parameters: $R_{acir} = 0.026\ \Omega$, $R_f = 32\ \Omega$, $N_f = 1520$ turns/pole. The magnetization curve for the generator is shown in Figure 12.23. The machine is operating at rated load, is separately excited from a 220-V source, and the equivalent demagnetizing mmf caused by armature reaction is 10.4 percent of the shunt field mmf. Determine (a) no-load voltage; (b) voltage regulation; (c) resistance and power rating of rheostat setting necessary to obtain rated voltage at rated conditions.

12–3/7 A noncompensated, separately excited shunt generator rated at 250 V, 50 kW, 3450 r/min, has the following parameters: $R_a + R_{IP} = 0.023\ \Omega$, $R_f = 324\ \Omega$, $N_f = 1896$ turns/pole. The magnetization curve for the generator is shown in Figure 12.23. The machine is operating at rated load, and the equivalent demagnetizing mmf due to armature reaction is 8.65 percent of rated shunt field mmf. Determine the no-load voltage at 3000 r/min.

12–4/7 A 60-kW, 240-V, 1750 r/min, self-excited, compensated shunt generator has the following parameters, expressed in ohms:

Armature	IP + CW	Shunt
0.0415	0.0176	44.6

The shunt field has 1653 turns/pole, and the magnetization curve is given in Figure 12.24. The generator supplies rated power at rated voltage when operating at rated speed with the shunt field rheostat set for 20.0 Ω. Determine (a) load current; (b) shunt field current; (c) armature current; (d) induced emf when operating at rated conditions; (e) no-load voltage, assuming speed and field rheostat are not changed; (f) critical resistance; (g) no-load voltage if operating with the rheostat adjusted to 13.6 Ω and the machine operating at 60 percent speed.

12–5/7 A 170-kW, 850 r/min, 250-V, self-excited shunt generator has the following parameters expressed in ohms:

Armature	Interpole	Shunt
0.0154	0.0065	29.0

The machine delivers rated power at rated voltage when operating at rated speed and the field rheostat set for 17.0 Ω. The shunt field has 1121 turns/pole, and the magnetization curve in Figure 12.24 applies. Determine (a) induced emf at rated load; (b) no-load voltage; (c) voltage regulation; (d) critical field resistance; (e) no-load voltage if the rheostat is set for 9.0 Ω.

12–6/7 A six-pole, self-excited shunt generator has an output rating of 500 kW and 240 V at a speed of 1200 r/min. The combined resistance of the armature and interpole windings is 0.00475 Ω, and the brush drop is insignificant. The resistance of the shunt field and field rheostat are 15.2 Ω, and 7.80 Ω, respectively. The shunt field winding has 508 turns/pole, and the

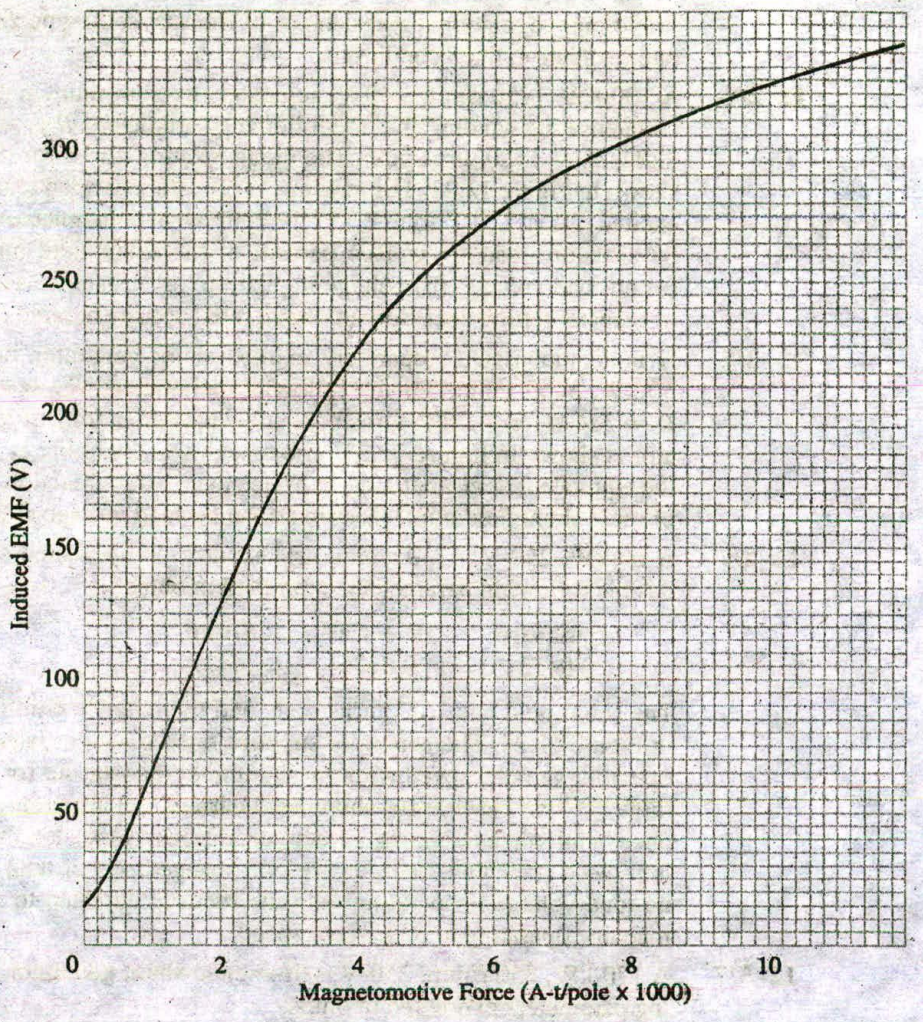


FIGURE 12.24
Magnetization curve for Problems 12–4/7 through 12–8/8.

magnetization curve in Figure 12.24 applies. Assuming the generator is delivering rated output, determine (a) load current; (b) shunt field current; (c) armature current; (d) induced emf; (e) no-load voltage; (f) voltage regulation; (g) frequency of the voltage generated in the armature; (h) no-load voltage if the rheostat is not changed, but the speed is cut in half; (i) critical resistance of the field circuit when operating at 1200 r/min; (j) losses in the armature circuit, shunt field winding, and rheostat when operating at rated conditions; (k) required driving torque of the prime mover if the generator is to deliver rated power at rated speed and rated voltage. Neglect windage and friction losses.

12–7/8 A 125-kW, 250-V, 1450 r/min, self-excited, cumulative-compound generator has the following parameters:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.02776	0.00808	0.00372	32.3
turns/pole			3	927

The rheostat is set for 13.2 Ω when operating at rated conditions. The magnetization curve in Figure 12.24 applies. Determine (a) rated load current; (b) shunt field current; (c) armature current; (d) induced emf at rated conditions; (e) no-load voltage; (f) voltage regulation; (g) type of compounding. (h) If the series field is disconnected because of damaged insulation, can the machine be operated as a shunt machine and obtain rated operating conditions through field-rheostat adjustment?

12–8/8 A 320-kW, 850 r/min, 250-V, self-excited, cumulative-compound generator is operating at rated conditions with the field rheostat set for 8.80 Ω. The magnetization curve in Figure 12.24 applies and the generator parameters are:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.0131	0.00380	0.00175	27.2
turns/pole			2	630

Determine (a) load current; (b) shunt field current; (c) armature current; (d) no-load voltage; (e) voltage regulation; (f) critical resistance; (g) maximum no-load voltage attainable by rheostat adjustment; (h) total electrical losses at rated load.

12–9/9 A self-excited compound generator delivers its rated 400 kW at 500 V and 850 r/min, and the shunt field rheostat is set for 24 Ω. The generator parameters are:

	Armature	IP + CW	Series	Shunt
Resistance, Ω	0.01754	0.005105	0.002351	80

Determine (a) resistance of a diverter that will reduce the current in the series field to 365 A when operating at rated armature current; (b) power loss in the diverter.

12–10/9 A 480-V, 720 r/min, 500-V, self-excited compound generator has the following parameters:

	Armature	Interpole	Series	Shunt
Resistance, Ω	0.01432	0.00501	0.00216	82

The generator supplies rated load when operating at rated speed and the field rheostat is set for 18.2 Ω. If a series-field diverter of 0.00321 Ω is installed, and the shunt field rheostat is adjusted so that the generator is delivering its rated armature current, determine (a) voltage drop across the diverter; (b) current in the series field; (c) power loss in the diverter.

12–11/14 Two undercompound generators, *A* and *B*, are operating in parallel at 125 V and take equal shares of a 1000-A bus load. Each machine has a rating of 200 kW at 125 V. The voltage regulation of machine *A* is 6 percent,

and that of machine *B* is 4 percent. If the bus load increases to 1800 A, determine (a) new bus voltage; (b) division of bus load between machines.

12–12/14 Two 500-kW, 250-V, undercompound generators *A* and *B* are operating in parallel. The voltage regulation of the machines are 2 and 3 percent, respectively. Both machines are operating at rated load and 250 V. Determine (a) new bus voltage; (b) division of load between machines when the total bus load drops to 2800 A.

12–13/14 Two DC generators are operating in parallel and take equal shares of a 900-kW bus load at 555 V. Generator *A* is rated at 500 kW, 600 V, and 3 percent regulation. Generator *B* is rated at 750 kW, 600 V, and 5 percent regulation. If the bus load drops to 1000 A, determine (a) new bus voltage; (b) current supplied by each machine.

12–14/14 Two identical 1000-kW, 600-V DC generators, whose regulation is 4 percent, are operating in parallel and take equal shares of the bus load. The bus load is 900 kW at 620 V. If one generator tripped off the line, determine (a) the voltage of the remaining machine; (b) voltage of the tripped machine.

12–15/14 Three 240-V DC generators are operating in parallel and taking equal shares of a 3000-A, 240-V bus load. The ratings of the generators are:

	A	*B*	*C*
Regulation (%)	2	4	6
Rated power (kW)	400	300	200

If the total bus load drops to 2000 A, determine (a) bus voltage; (b) current supplied by each machine.

13

Control of Electric Motors

13.1 INTRODUCTION

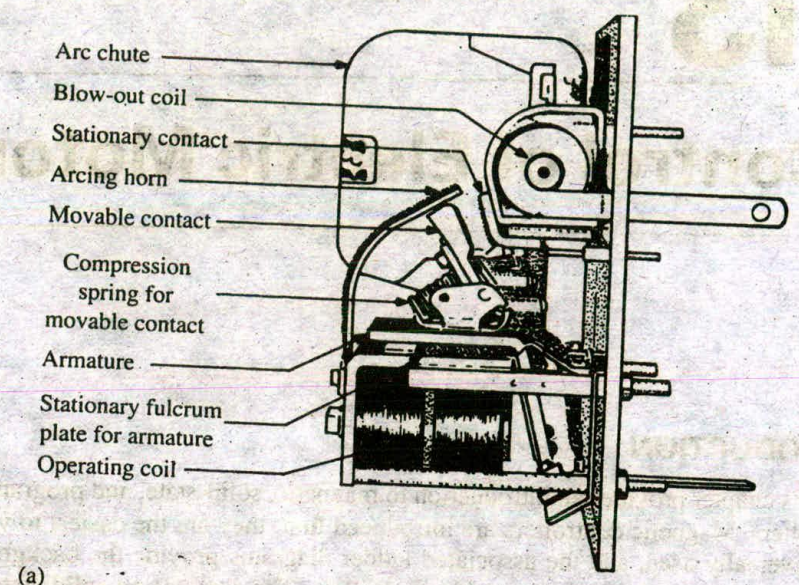
This chapter provides an introduction to magnetic, solid-state, and programmable controllers. Magnetic controllers are introduced first; they are the easiest to visualize, are universally used, and the associated ladder diagrams provide the background for future applications to programmable controllers. The sections on solid-state controllers cover only power circuits; firing circuits are beyond the scope of this text. The brief section on programmable controllers provides some insight into this expanding field.

13.2 CONTROLLER COMPONENTS

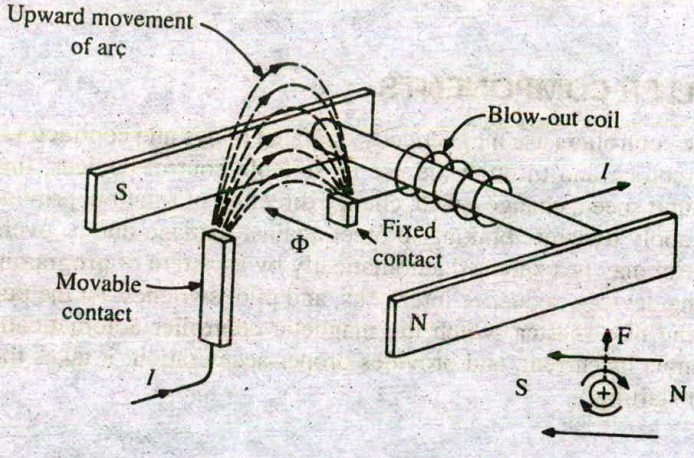
Magnetic controllers use magnetically operated relays and contractors to start and stop electric motors, and through the use of suitable control devices, limit current, limit torque, limit speed, change speed, change direction of rotation, provide uniform acceleration, apply dynamic braking, protect against damage due to overload, and so on. The control may be exercised automatically by a system of programming, using electric timing devices, sequence interlocks, and pilot switches. At the push of a button or the closing of a master switch the magnetic controller automatically starts the machine, limits its current, and provides proper acceleration; it takes the guesswork out of motor starting.

Magnetic Contactors

A magnetic contactor is a magnetically operated switch that serves to close or open an electric circuit. A cutaway view of a DC magnetic contactor is shown in Figure 13.1(a). When energized, the operating coil pulls on the armature, causing the contacts to close. The blow-out coil is connected in series with the stationary contact and provides a magnetic flux to "blow" the arc up the chute, where it is extinguished by elongation and cooling when the contacts are opened. Wear on the stationary and movable contacts is reduced by the arcing horn, which takes the brunt of the burning. The blow-out coil shifts the arc to the arcing horn and the upper curved part of the stationary



(a)



(b)

FIGURE 13.1
Magnetic contactor: (a) cutaway view of a DC contactor (Courtesy GE Industrial Systems); (b) operation of magnetic blow-out.

contact, where it is extinguished. Figure 13.1(b) illustrates the behavior of the magnetic blow-out. Current in the coil sets up a magnetic flux in the north and south direction, as shown. When the contacts separate, an arc is established in a direction perpendicular to the flux of the field. The resultant motor action pushes the arc upward, stretching it until it breaks. The upward movement of the arc may be verified by applying the flux bunching rule; see inset in Figure 13.1(b).

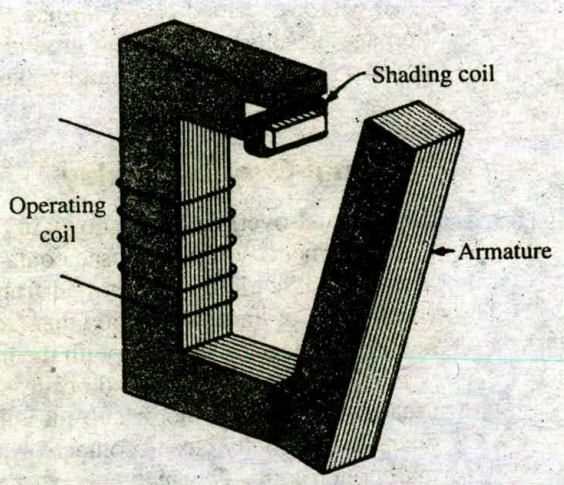


FIGURE 13.2
Magnetic circuit for an AC contactor, showing the shading coil.

Alternating-current contactors and relays also are equipped with arcing horns and blow-out coils. The magnetic core, however, is laminated to reduce eddy currents, and a pole shader is used to prevent the magnetic flux from dropping to zero each time the current in the coil goes through zero. The pole shader, shown in Figure 13.2, is a one-turn, short-circuited coil on the face of the core. The shading coil acts as the short-circuited secondary of a transformer. In accordance with Lenz's law, the shading coil causes the flux in the shaded part of the pole to lag behind the flux in the nonshaded part. This prevents the net flux from falling to zero, and thus reduces armature vibration (chatter).

Relays

A relay is a device used to control the operation of a magnetic contactor or other device. Relays operate as a function of current, voltage, heat, and pressure, and supply the "intelligence" that is necessary to provide automatic acceleration, protect against overload, undervoltage, excessive speeds, excessive torque, etc.

13.3 MOTOR-OVERLOAD PROTECTION

Excessive current drawn by an overloaded motor will, if allowed to continue for sufficient time, result in dangerous overheating of both motor and control. Correctly sized motor-overload relays with the proper time-current characteristics provide protection against sustained overloads, and yet permit the short-duration, high locked-rotor current necessary for motor starting. They also protect against overheating due to overcurrents caused by a stalled rotor, low-voltage, low-frequency, unbalanced voltages, and some other types of motor faults. Although such overcurrents are of relatively low magnitude compared with short circuits, they will, if sustained, shorten the life of the insulation.

Motor-overload relays do not protect against short circuits or grounds. Protection against short circuits and grounds must be provided by branch-circuit protection devices such as fuses or circuit breakers.[1]

Thermal-Overload Relay

The thermal-overload relay shown in Figure 13.3(a) consists of a bimetallic element, a heater element, normally closed contacts, normally open contacts, and a reset button.[2] The bimetallic element is formed from two strips of dissimilar metals with different coefficients of linear expansion that are bonded together to form a single element. The heater is connected in series with the motor and simulates the I^2R heating of the motor windings. Should an overload occur, the increase in heater temperature caused by the greater-than-normal motor current will cause the bimetallic element to deflect. This opens the normally closed contacts, which de-energizes the motor, and closes the normally open contacts, which energizes an alarm circuit. The reset arm is used to manually reset the relay contacts after the bimetallic element has cooled.

Figure 13.3(b) shows how the heater and associated normally closed contacts are connected into a controller circuit. Controllers for large motors use current transformers (CTs) to provide proportional but lower values of current to a proportionally lower rated heater; this is shown with broken lines in Figure 13.3(b). An overload of sufficient duration causes normally closed contact OL to open. This de-energizes coil M, causing the three normally open M contacts to fall to the open position.

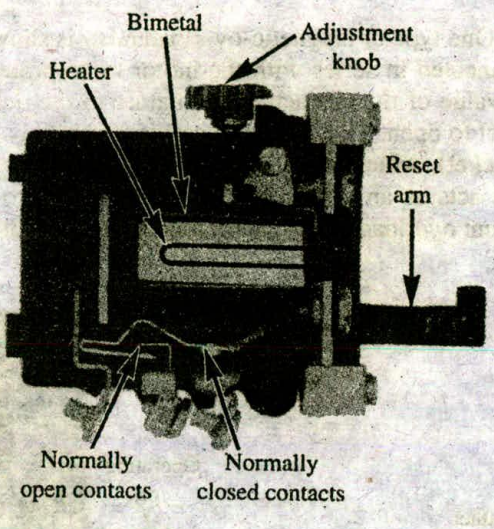
The approximate current-time characteristics for tripping and resetting the bimetallic relay are shown in Figure 13.3(c). Note that the tripping time decreases with increasing current (inverse-time characteristic), but the reset time increases with increasing current. For the characteristics shown, an overload of 400 percent rated heater current causes tripping somewhere between 20 and 30 s. The resetting time for the specific family of relays, however, is roughly between 75 and 140 s, during which time the motor is at rest and cooling. The overcurrent relay shown in Figure 13.3(a) is provided with an adjustable setting to permit tripping at approximately 15 percent above or 15 percent below the heater rating.

The selection of an overcurrent protective device is determined by the type of overload the machine may encounter. Motors that drive fans, pumps, and most machine tools require protection against sustained overloads that may cause excessive heating of the insulation; such motors are generally protected by time-delay thermal-overload relays, whose tripping time decreases with increasing overload. In other applications, such as motor-driven elevators, winches, traction motors, and other loads that are subject to jamming, instantaneous magnetic-overload relays are used. Jamming of a motor will cause the current to rise to and hold at its locked-rotor value; if not immediately disconnected, the insulation may be destroyed.

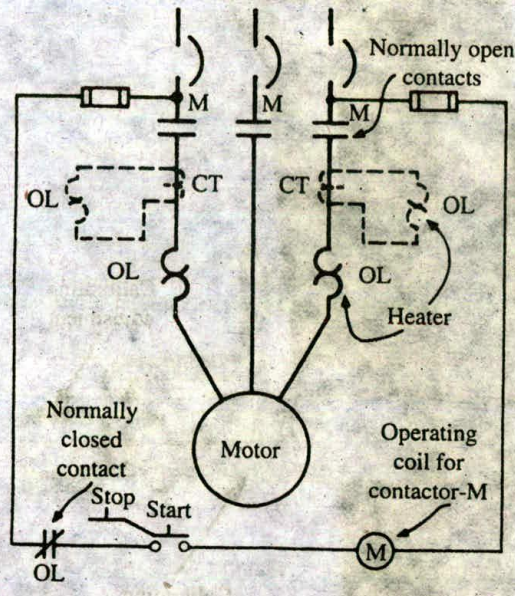
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[1] See Section 430 of the National Electrical Code (NEC) for proper selection of running-overload protection of motors, branch-circuit protection, and sizing of branch-circuit conductors [4],[5].

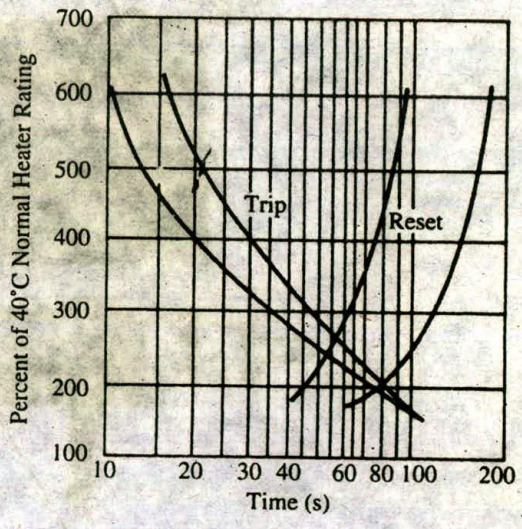
[2] See the references for other types of motor-overload relays, such as solder-pot and heater, solenoid and dashpot, and solid-state devices [3].



(a)



(b)



(c)

FIGURE 13.3
Thermal-overload relay (Courtesy GE Industrial Systems): (a) cutaway view; (b) circuit diagram; (c) current-time characteristics for tripping and resetting.

One type of magnetic-overload relay is shown in Figure 13.4. The operating coil is connected in series with the motor to be protected. When an overload occurs, the high value of flux attracts the armature to the pole face, causing the normally closed contact to open. The operating coil is supported on a heavy copper tube (called a copper jacket), which is in turn mounted on the magnetic core of the relay. The copper jacket acts as an inductive time-delay device to prevent the relay from tripping on transient overloads. Normal motor currents do not cause sufficient flux to trip the relay.

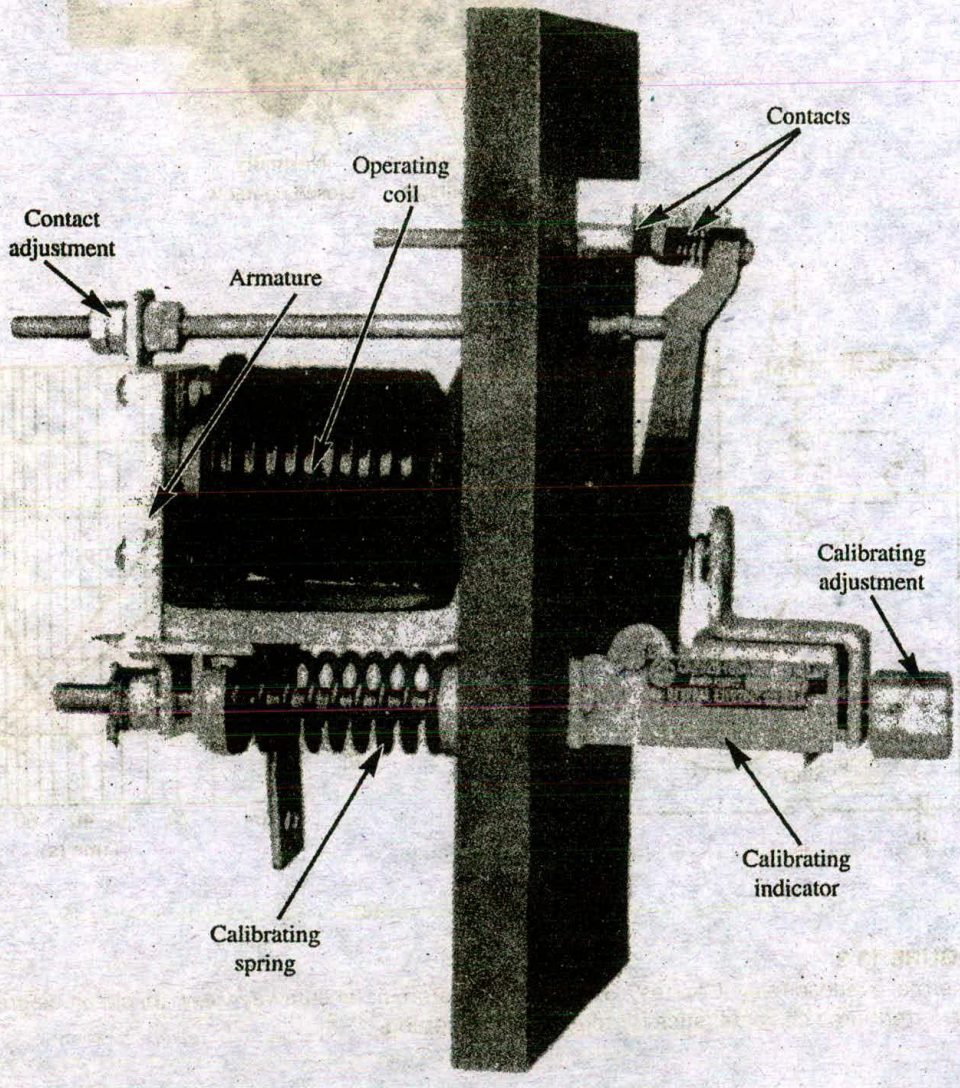


FIGURE 13.4
Instantaneous overcurrent relay. (Courtesy GE Industrial Systems)

13.4 CONTROLLER DIAGRAMS

The two general classifications of controller diagrams are the *connection diagram* and the *elementary diagram.*[3] The connection diagram, shown in Figure 13.5, shows the actual physical layout of the controller components and the location and routing of each wire. The connection diagram facilitates the location of the components for repair, replacement, or adjustment. Note that the power circuit, which carries the motor current, is drawn with heavy lines to indicate larger cross-section copper. The control circuit is drawn with light lines. The panel heater is used in damp environments to prevent condensation of moisture.

The elementary diagram, shown in Figure 13.6, is a simplified drawing that shows how the system works. The elementary diagram is often referred to as a *ladder diagram,* because the horizontal lines are like rungs and the two outside power lines are like the rails. The elementary diagram has a *power circuit* and a *control circuit.* The power circuit includes the motor components, starting resistors, and power contacts. The control circuit, also called the *logic circuit,* includes push buttons, operating coils, overload contacts, relay contacts, and limit switches that provide the logic and commands for operation of the motor. Note that the control components of a device shown in the connection diagram of Figure 13.5 are separated in the ladder diagram. For example, the three components of relay 2A in Figure 13.5 are shown separated in Figure 13.6. To avoid confusion, all components of a device are assigned the same letter designation in both the connection diagram and the ladder diagram. Furthermore, the numbering of the terminals in the ladder diagram corresponds to the numbering in the connection diagram. The numbering also serves as a guide for determining points of equal potential and is of considerable assistance when troubleshooting; terminals with the same numbering should have like potentials regardless of contactor position.[4]

The order of components in the ladder diagram is such that reading down the rungs, and from left to right, shows the sequence (or logic) of control operation. The ladder diagram is a simplified diagram that is easier to read than the connection diagram, and is easier to diagnose if malfunctioning occurs.

13.5 AUTOMATIC SHUTDOWN ON POWER FAILURE

All motor control circuits provide automatic shutdown on power failure, and either resequence the logic for automatic restarting when power is restored (undervoltage release) or remain in the off condition until manually restarted (undervoltage protection).

Undervoltage Release

The control circuit illustrated in Figure 13.7(a) provides for the automatic disconnection of the motor from the line in case of voltage loss and its automatic reconnection when voltage is restored. This type of control is generally applied to vital machinery,

[3]See Appendix D for graphic symbols used in controller diagrams.

[4]See Reference [2] for troubleshooting and maintenance of magnetic controllers.

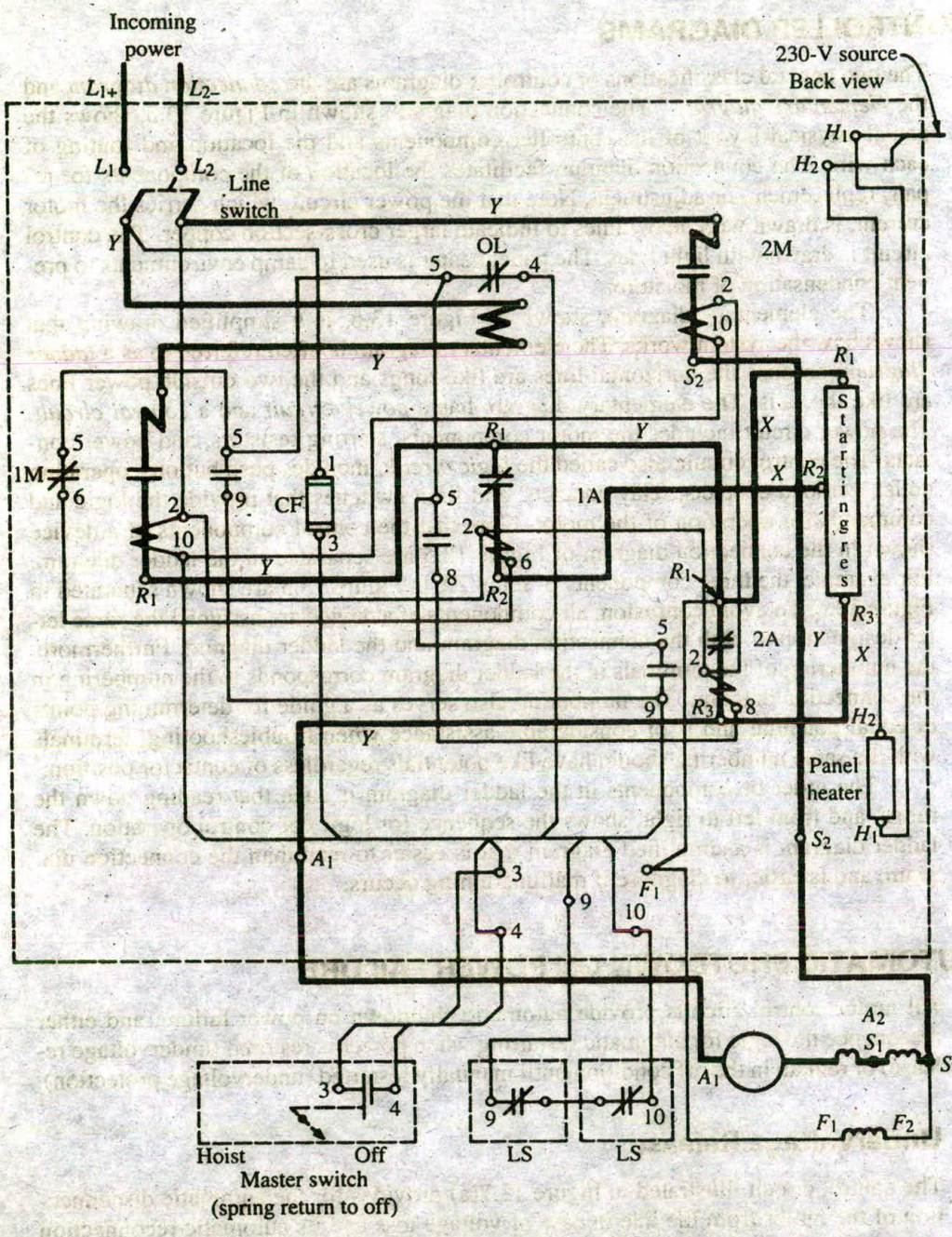


FIGURE 13.5
Typical connection diagram for a motor controller. (Courtesy GE Industrial Systems)

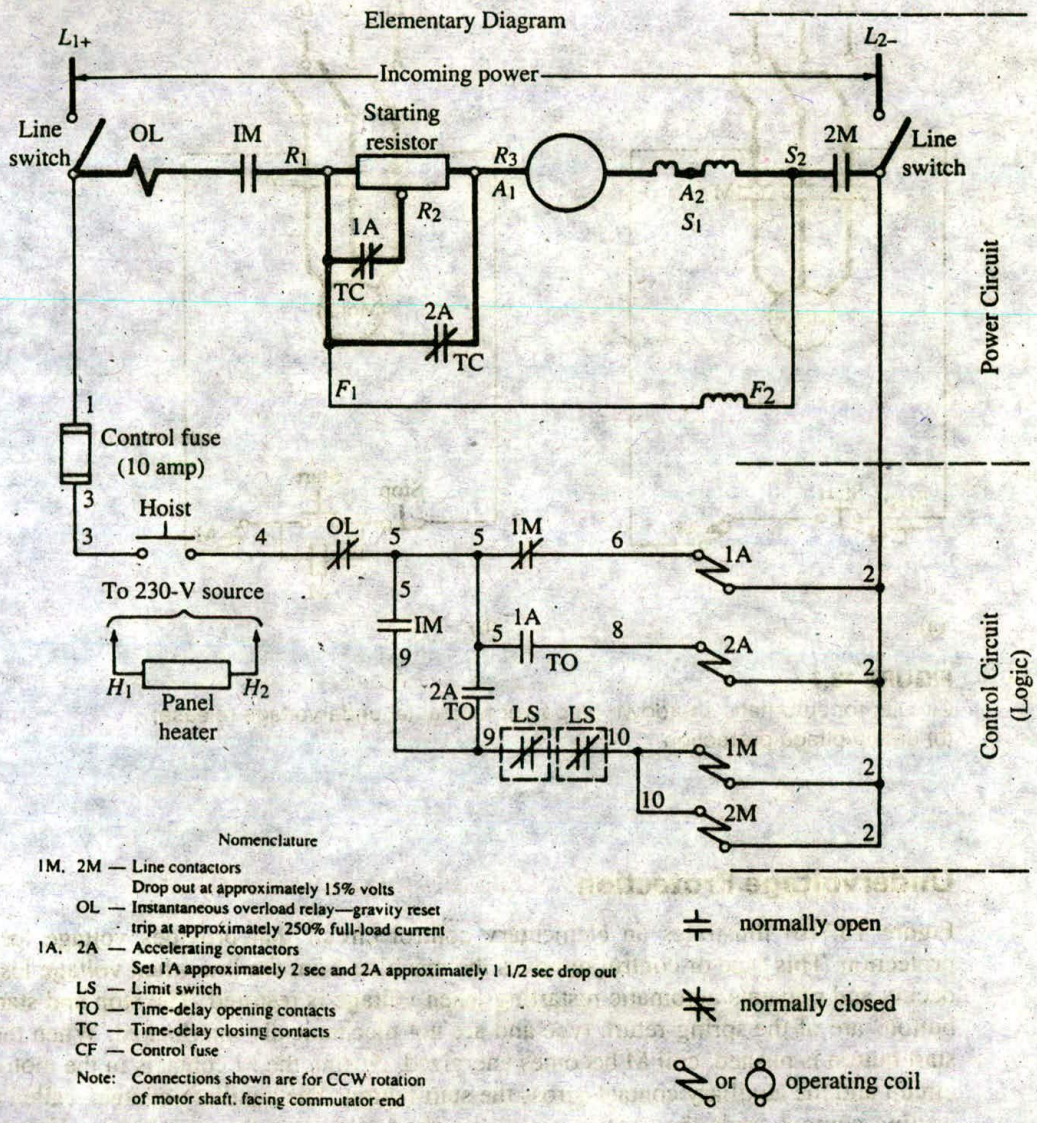


FIGURE 13.6
Elementary diagram for the controller in Figure 13.5. (Courtesy GE Industrial Systems)

in which it is imperative that the operation be automatic. Sump pumps and fire pumps are some of its applications. A non-spring-return type of push button is used in undervoltage release circuits. When the start button is pushed, it remains depressed and causes the control circuit to stay closed until the stop button is pushed. Hence, if voltage loss causes contactor M to open, the restoration of voltage will result in automatic reclosure.

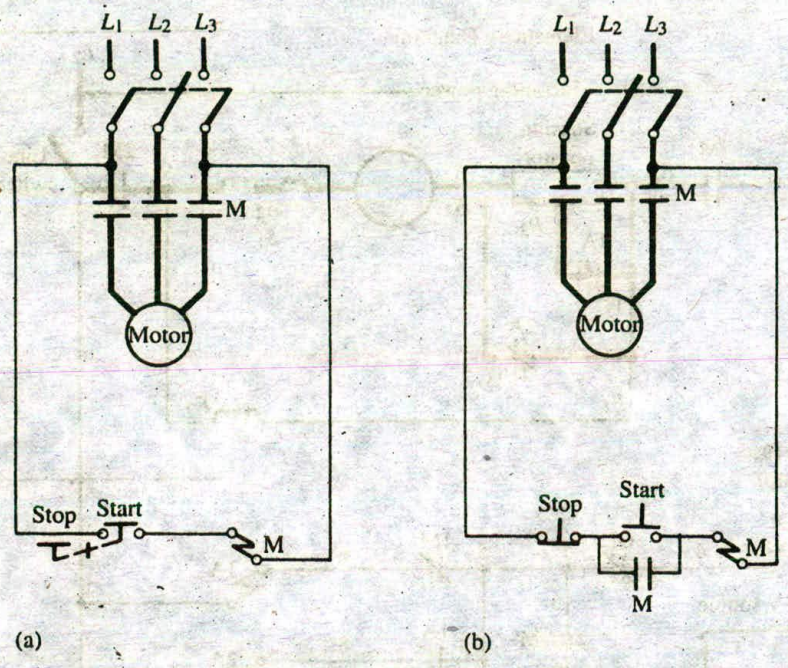


FIGURE 13.7
Circuits for automatic shutdown on power failure: (a) undervoltage release; (b) undervoltage protection.

Undervoltage Protection

Figure 13.7(b) illustrates an elementary control circuit that provides voltage loss protection. This type of control removes the machine from the line when voltage loss occurs and prevents automatic restarting when voltage is restored. The stop and start buttons are of the spring-return type and are not mechanically interlocked. When the start button is pushed, coil M becomes energized, closing the M contacts in the motor circuit and the auxiliary contact across the start button. The auxiliary contact, called a *sealing contact*, seals the starting circuit by short circuiting the start button. Hence, coil M remains energized after the start button is pushed and released. In the event of voltage loss, coil M is no longer energized, and the contacts fall to the normally open position. The motor will not start when voltage is restored unless the start button is pushed again. This type of control is generally applied to all nonvital machinery. It is particularly adaptable to those drives in which the unexpected starting of a saw, shaper, or other machine tool presents a serious hazard to operating personnel.

Note: Standard undervoltage protection and undervoltage release devices are not designed for dropout at any specific voltage reduction; their function is protection against voltage loss.

13.6 REVERSING STARTERS FOR AC MOTORS

A control circuit for an AC reversing across-the-line starter equipped with overload and voltage-loss protection is shown in Figure 13.8. The two forward buttons are mechanically interlocked, and the two reverse buttons are mechanically interlocked. Pushing the forward button closes its normally open contact and opens its normally closed contact. If the reverse button is pushed while the machine is running in the forward direction, the normally closed reverse button will open and de-energize the forward coil.

Coils F and R operate the respective directional contacts in the motor circuit and the respective sealing contacts in the control circuit.

13.7 TWO-SPEED STARTERS FOR AC MOTORS

The magnetic-starter circuit for a two-speed, two-winding, three-phase induction motor is shown in Figure 13.9. Each winding has its own overload protective device, an indication that the power and current ratings are different for the two speeds. An

FIGURE 13.8
Reversing controller for a three-phase induction motor.

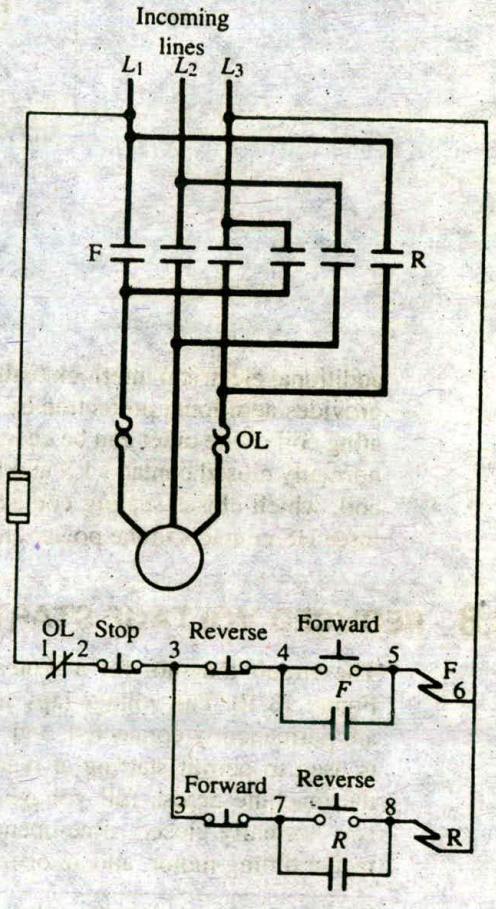
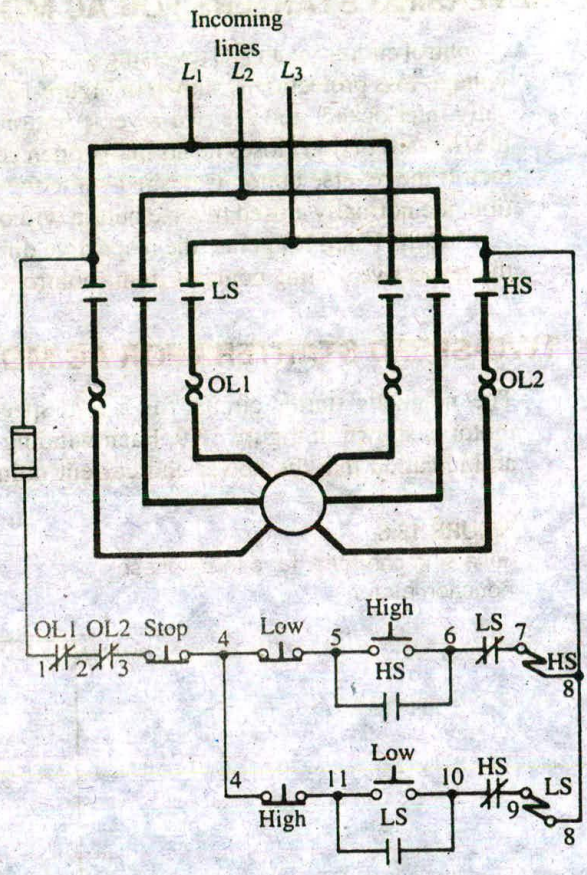


FIGURE 13.9
Controller for a three-phase, two-speed, two-winding induction motor.



additional electrical interlock (called a *sequence interlock*) on each magnetic contactor provides additional protection by requiring one contactor to drop out before the operating coil of the other can be energized. The sequence interlocks in Figure 13.9 are the normally closed contacts LS and HS. Pushing the high-speed button energizes the HS coil, which closes sealing contact HS, opens sequence interlock HS, and closes the three HS contacts in the power circuit.

13.8 REDUCED-VOLTAGE STARTERS FOR AC MOTORS

The circuit diagram for a typical three-phase, reduced-voltage starter is shown in Figure 13.10. The voltage taps are selected on the basis of the starting requirements, are permanently connected, and are not adjustable by the operator. Timing relay TR is used to permit starting at reduced voltage for a preset time, and then to connect the machine across full voltage. The timing relay has one normally open contact, two normally closed, time-opening contacts, one normally open, time-closing contact, a timing motor, and an operating solenoid.[5] When the start button is pushed, the

[5]Timing may be accomplished by dashpot, solid-state, mechanical (using an escapement mechanism), thermal, motor-drive, or pneumatic means.

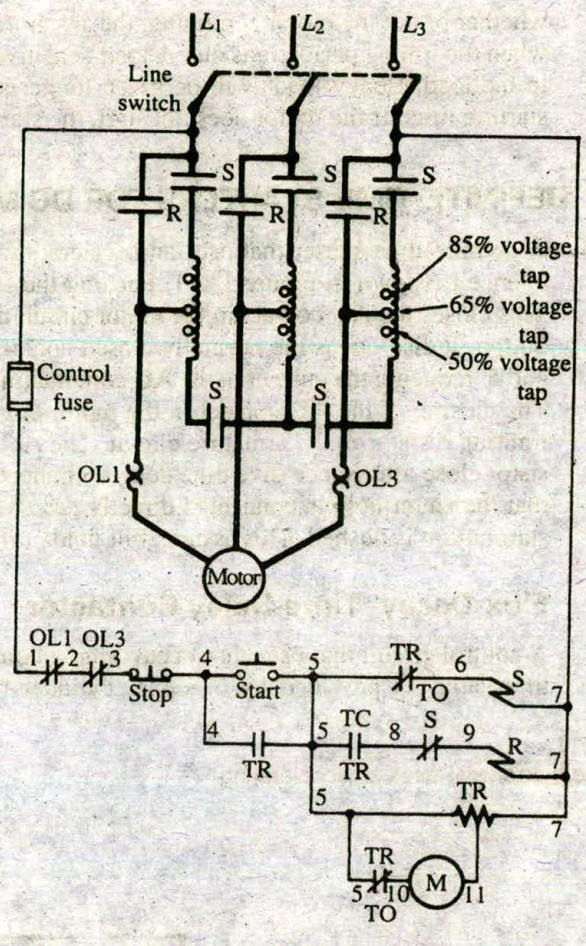


FIGURE 13.10
Controller for reduced-voltage starting of a three-phase induction motor.

current in the control circuit takes three parallel paths: through coil S to energize the autotransformer; through the timing motor to time the starting operation; and through relay coil TR to seal the starting circuit. Closing of contactor S starts the motor at reduced voltage. After a time delay of 1 to 10 s, adjustable, the timing motor causes the time-delay contacts to operate. Coil S is de-energized, the R coil becomes energized, and the circuit to the timing motor opens. The R coil closes the running contacts, connecting the motor across full voltage.

13.9 CONTROLLERS FOR DC MOTORS

Direct-current motors above 3/4 hp are started with reduced voltage. The starters may be divided into two general classifications: definite-time starters and load-sensitive starters. A definite-time starter will remove the starting resistance from the armature circuit after a preset time has elapsed. Thus, regardless of the load on the shaft or

whether or not the motor is running, the armature will be connected across full voltage when the timing period runs out. A load-sensitive starter will adjust motor acceleration to the load. Heavy loads will be given longer starting time and lighter loads shorter starting time. If the motor does not start, the starting resistance will not be cut out.

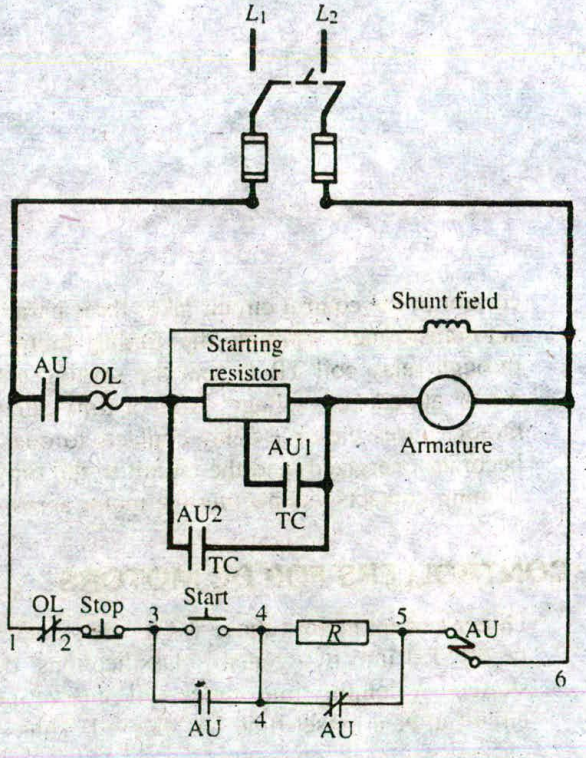
13.10 DEFINITE-TIME STARTERS FOR DC MOTORS

A definite-time starter that uses an accelerating unit (AU) to provide the starting sequence is shown in Figure 13.11. Pushing the start button causes current in coil AU. This closes the AU contact in the motor circuit and the sealing contact across the start button. It also opens the normally closed contact across the resistor between points 4 and 5, reducing the current in the AU coil, making it more sensitive to reduced voltage. The closing of the AU contact in the motor circuit starts the machine with a current-limiting resistor in the armature circuit. The AU contacts connected to the starting resistor close after successive time delays, connecting the armature across the line. Note that the shunt field is connected directly across the line with no time delay when the start button is pushed. This assures full field current, and thus a high starting torque.

Flux-Decay, Time-Delay Contactor

A control circuit that uses flux-decay timing contactors is shown in Figure 13.12. The time delay is provided by a copper cylinder (called a copper jacket) surrounding

FIGURE 13.11
Definite-time starter that uses an accelerating unit to start a DC motor.



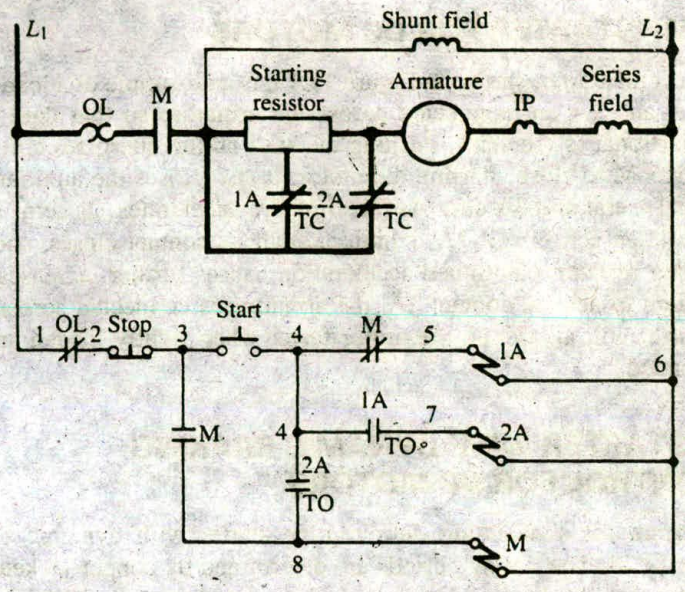


FIGURE 13.12
Definite-time starter that uses flux-decay, time-delay contactors to accelerate a DC motor.

the iron core, around which the operating coil is wound. The time-delay contactor is normally closed, and opens when the coil is energized. When the coil is de-energized, however, the copper jacket delays the decay of flux. Thus, the contact falls to the closed position after a time delay.

When the coil is de-energized, its magnetic field does not instantaneously fall to zero. As the field starts to collapse, it induces an emf in the copper jacket. In accordance with Lenz's law, the induced emf and resultant current in the copper jacket will be in a direction to oppose the decay of flux. The gradual reduction in flux will cause a time delay of several seconds before the contactor closes. The time delay may be adjusted by changing the reluctance of the magnetic circuit, changing the copper jacket, and/or adjusting the spring tension.

Referring to Figure 13.12, when the start button is pushed, current in coil 1A causes the simultaneous closing of auxiliary contact 1A and the opening of resistor-shorting contact 1A. Closing of auxiliary contact 1A energizes coil 2A, which simultaneously opens resistor-shorting contact 2A and closes auxiliary contact 2A. Closing of auxiliary contact 2A allows current in coil M. Coil M closes the motor line contactor M, which starts the motor with all of the starting resistance in series with the armature circuit. At the same time, auxiliary contact M between points 3 and 8 seals the starting circuit, and auxiliary contact M between points 4 and 5 opens. This de-energizes coil 1A, starting the timing cycle for motor acceleration. After a time delay of several seconds, resistor-shorting contact 1A closes, increasing the motor speed, and auxiliary contact 1A opens de-energizing coil 2A. After another time delay, resistor-shorting contact 2A closes, connecting the machine across full voltage.

13.11 COUNTER-EMF STARTER FOR DC MOTORS

The circuit for a cemf starter, shown in Figure 13.13, is an example of a load-sensitive starter. Coils 1A and 2A are connected across the armature so that their magnetic strength is proportional to the cemf. Pushing the start button energizes coil M, causing power contacts M to close, starting the motor. It also closes the auxiliary contact M in series with 1A coil and 2A coil. As the armature accelerates, its cemf increases, and when the voltage across coil 1A is high enough its contact closes, shorting out part of the starting resistor. Continued acceleration causes further increases in cemf. When high enough to actuate contact 2A, the armature is connected across the line. This type of starter will accelerate the motor faster when lightly loaded and slower when heavily loaded.

13.12 REVERSING STARTER WITH DYNAMIC BRAKING AND SHUNT FIELD CONTROL FOR DC MOTORS

The circuit diagram for a reversing definite-time starter with dynamic braking is shown in Figure 13.14. The timing periods are determined by copper-jacketed timing relays 1A and 2A, and reversing is accomplished by contactors 1R, 2R, 1F, and 2F in the armature circuit. The 1F *back coil* and the 1R *back coil* are magnetic interlocking coils connected across the armature. These holdback coils are excited by the armature cemf and prevent the application of reverse power until the motor slows down. The application of reverse power to a motor before it stops is called *plugging*. The physical layout of the operating coil and its corresponding back coil are shown in Figure 13.15.

Referring to Figure 13.14, if the motor is running in the forward direction and the reverse button is pushed, the forward contactors 1F and 2F will drop out, but the 1R operating coil will not be able to close its contact until released by the 1R back

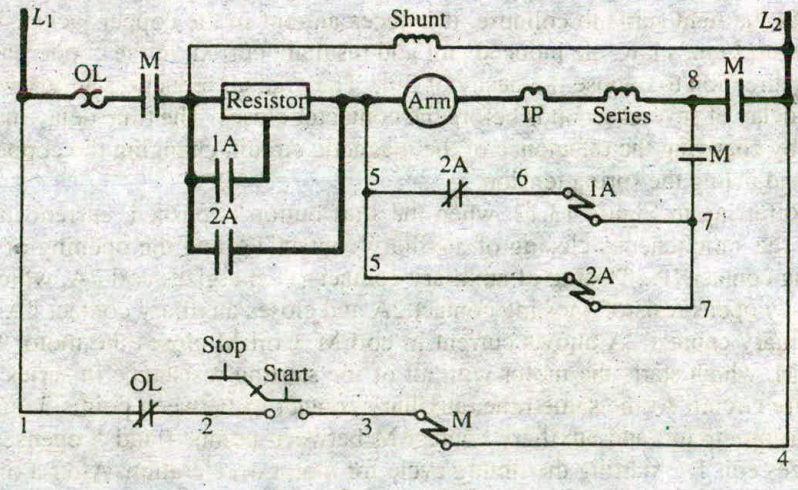


FIGURE 13.13
Counter-emf starter.

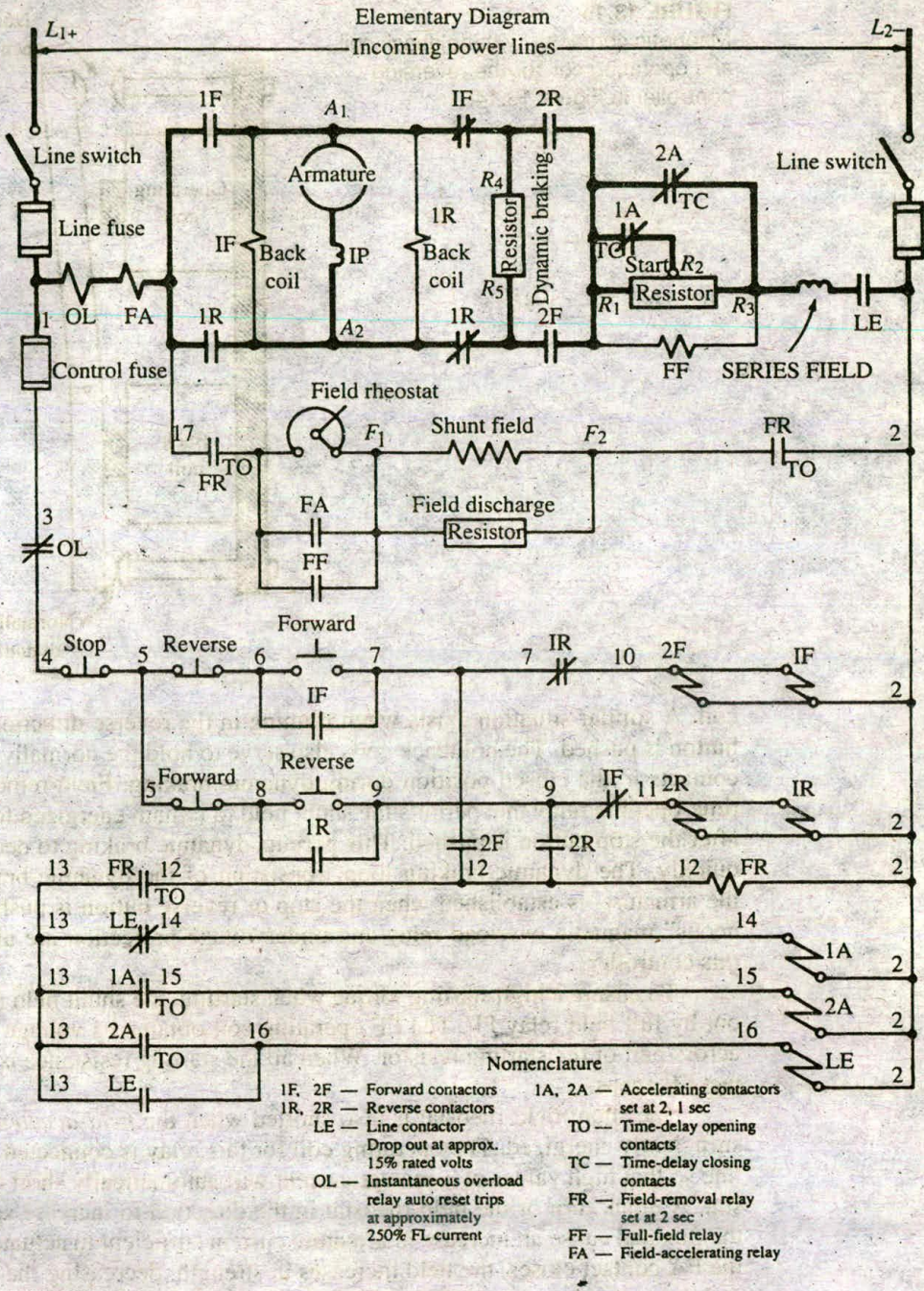


FIGURE 13.14
Reversing controller with dynamic braking. (Courtesy GE Industrial Systems)

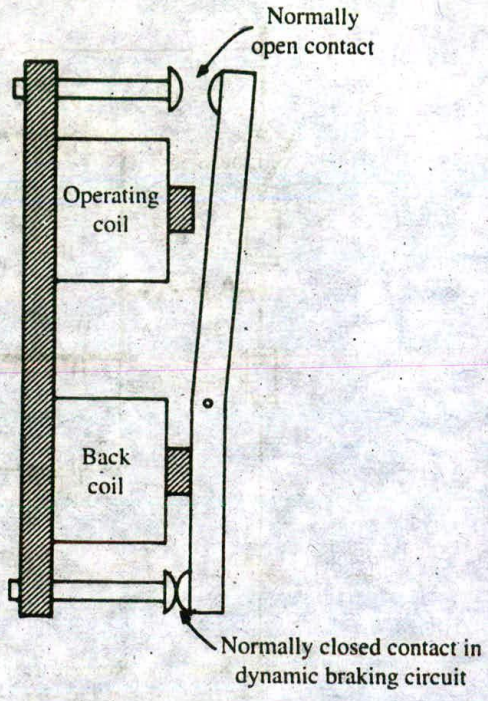


FIGURE 13.15
Magnetic contactor with holdback coil and operating coil for the reversing controller in Figure 13.14.

coil. A similar situation exists when running in the reverse direction and the forward button is pushed. The holdback coils also serve to hold the normally closed 1F and 1R contacts in the closed position during dynamic braking. Field-removal relay FR is a time-opening relay that permits the shunt field to remain energized for several seconds after the stop button is pushed. This permits dynamic braking to decelerate the motor quickly. The dynamic-braking loop, consisting of the dynamic-braking resistor and the armature, is established when the stop or reverse button is pushed. An "instantaneous" magnetic overload relay and undervoltage protection are also provided with this controller.

To ensure a high starting torque when starting, the shunt field rheostat is shorted out by full field relay FF. The FF operating coil obtains its voltage from the IR drop across part of the starting resistor. When all the starting resistance is shorted out, contact FF opens.

The shunt field rheostat is also shorted when the *field-accelerating relay* FA is sufficiently energized. The operating coil for this relay is connected in series with the line so that high values of armature current will automatically short out the field rheostat. A quick turn of the field rheostat in the direction to increase speed will weaken the flux and cause an increase in armature current sufficient to actuate relay FA. When the FA contact closes, the field increases in strength, decreasing the armature current, and thus allowing contact FA to open again. The FA contact flutters in and out until the high transient current (instigated by operation of the field rheostat) is sufficiently reduced, at which time contact FA remains open.

13.13 SOLID-STATE CONTROLLERS

Solid-state controllers use diodes, transistors, thyristors (SCRs), triacs, and other solid-state devices in different configurations to start, stop, reverse, brake, provide soft starting, and adjust the speed of electrical machinery. Since solid-state devices have no moving parts, they require considerably less maintenance than their magnetic counterparts. Furthermore, the absence of arcing and/or sparking makes them attractive for applications in explosive atmospheres. Solid-state devices may be used effectively and efficiently for the control of machinery from fractional horsepower units to tens of thousands of horsepower.

13.14 THYRISTOR CONTROL OF MOTORS

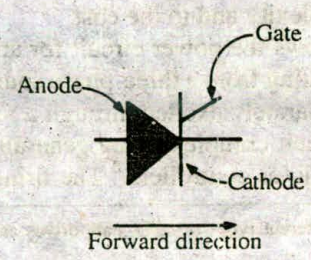
The thyristor, shown symbolically in Figure 13.16, is a silicon-controlled rectifier (SCR) that acts as a combined switch and diode. The SCR has two states, on and off. When in the off state, no current can pass in either direction. When in the on state, the SCR acts as a diode, permitting current only in the forward direction.

An SCR remains in the off state, called the *blocking state,* until its anode *and* gate are both positive with respect to the cathode. When both of these conditions are met the SCR "fires," and current conduction begins.

A basic SCR circuit is shown in Figure 13.17(a); the gate firing circuit, called a triggering circuit, contains the complex circuitry that determines when and for how long the gate is to be positive.

When the gate firing circuit triggers the SCR, it is switched to the on state, as shown in Figure 13.17(b); a pulse of only a few microseconds duration will switch on an SCR. Once fired, the SCR will remain in the on state, even after the gate circuit is opened; the load current keeps it in the on state. In effect, the SCR behaves like a latching contactor or latching relay. In order for the gate circuit to regain control, the anode current must cease. This may be accomplished by opening the switch in the anode circuit, by using an AC driving voltage in the anode circuit, or by forced commutation using a reverse-voltage impulse in the anode circuit. The process of turning off the thyristor is called *commutation.* Natural commutation occurs when the anode circuit is supplied by an AC driver. When using an AC driving voltage, the SCR switches to the off state each time the anode becomes negative, enabling the gate circuit to regain control.

FIGURE 13.16
Thyristor (SCR).



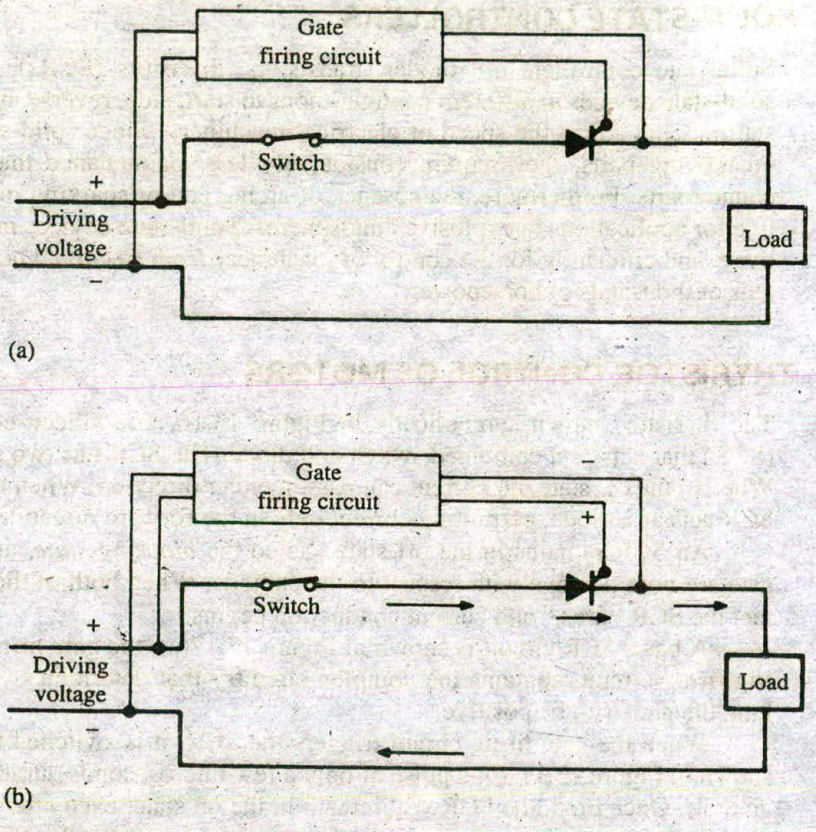


FIGURE 13.17
(a) Basic thyristor circuit; (b) thyristor in conducting state.

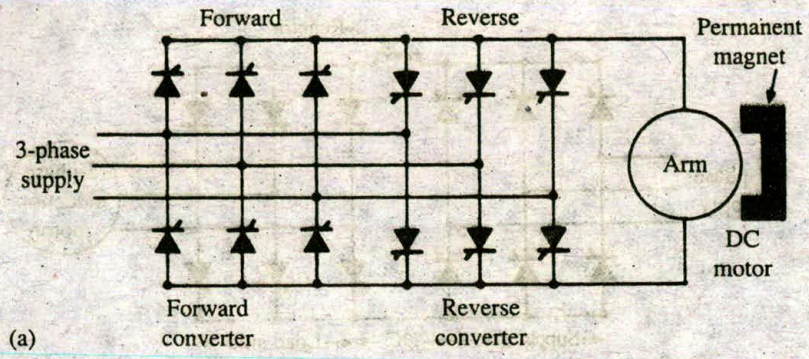
13.15 SOLID-STATE ADJUSTABLE-SPEED DRIVES

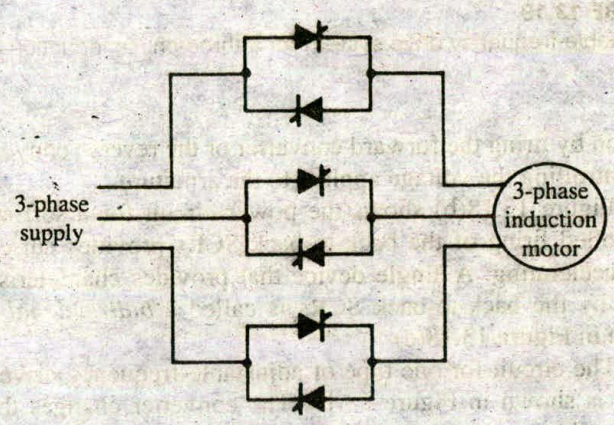
High-power, solid-state, adjustable-speed drives deliver precise speed control and high operating efficiency. The trigger circuits are controlled by microprocessors that switch the SCRs on and off in a programmed sequence that is easily varied by the operator.

The complexity of the firing circuit depends on the number of control features desired. Such features as soft start, speed control, reversing, torque limit, and current limit, all add to the complexity and to the cost.

Figure 13.18(a) shows the power circuit for an adjustable-speed, reversible DC motor drive system operating from a three-phase source. The field may be a permanent magnet, as shown, or separately excited through a rectifier. The firing circuits are not shown, and because of their complexity are generally not included in manufacturers' diagrams of solid-state motor controllers.[6] The firing circuits control the direction of

[6]For in-depth discussions of different types of solid-state drives and associated firing circuits see References [6],[7].





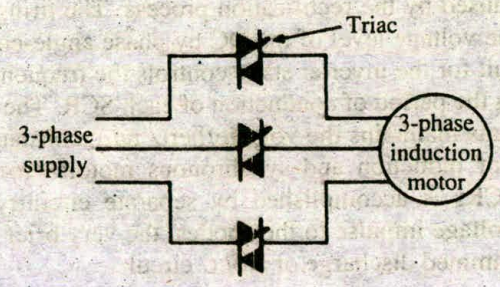


FIGURE 13.18
Thyristor power circuits: (a) adjustable-speed reversible drive system for a permanent-magnet DC motor; (b) soft-start motor controller with back-to-back SCRs for a three-phase induction motor; (c) soft-start motor controller with triacs for a three-phase induction motor.

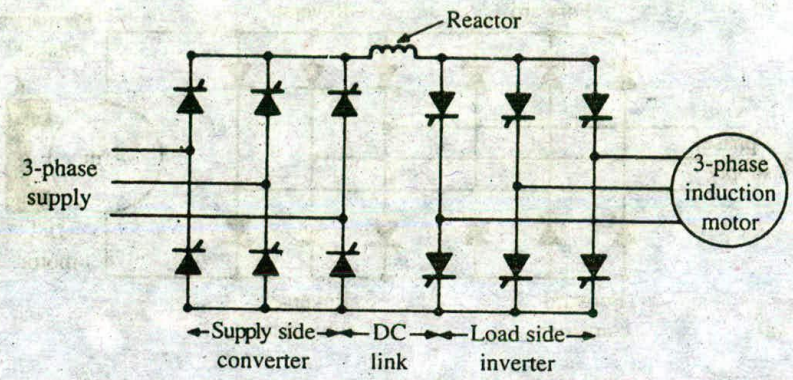


FIGURE 13.19
Adjustable-frequency drive system for a three-phase induction motor.

rotation by firing the forward converter or the reverse converter, and control the speed by controlling the voltage applied to the armature.

Figure 13.18(b) shows the power circuit for a soft start AC motor controller. Controlled firing of the back-to-back SCRs provides current limiting when starting and accelerating. A single device that provides characteristics similar to those provided by the back-to-back SCRs is called a *bidirectional thyristor* or *triac,* and is shown in Figure 13.18(c).

The circuit for one type of adjustable-frequency drive system for a three-phase motor is shown in Figure 13.19. The converter changes the fixed-frequency, fixed-voltage, three-phase input to DC, and the inverter changes the DC back to three-phase AC, whose frequency is controlled by the inverter firing circuits. The reactor in the DC link between the converter stage and the inverter stage serves to reduce harmonic currents caused by the rectification process. The firing circuit for the converter stage controls the voltage level of the DC by phase angle-control at the point of firing. The firing circuit for the inverter stage controls the frequency of the three-phase output by controlling the period of conduction of each SCR. The logic circuitry that controls the firing circuits maintains the voltage/hertz ratio constant, which is essential for proper operation of induction and synchronous motors (see Section 5.8). Turnoff of the inverter SCRs is accomplished by separate circuitry, not shown, that provides a negative-voltage impulse to the anodes; the very brief voltage pulse may be obtained by a programmed discharge of an *LC* circuit.

13.16 CYCLOCONVERTER DRIVES

A cycloconverter is a frequency converter that converts the incoming supply frequency to some other lower frequency. An elementary circuit for a cycloconverter drive is shown in Figure 13.20. It uses three dual converters to convert the three-phase input line frequency to an adjustable lower frequency of nearly sinusoidal waveform. The fixed-frequency, fixed-voltage AC input is converted to a variable-frequency,

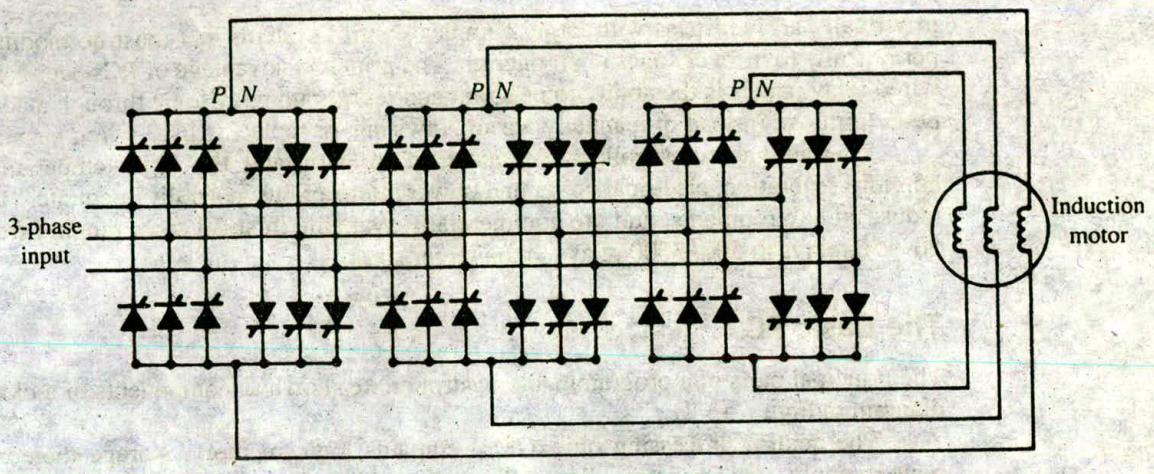


FIGURE 13.20
Cycloconverter supplying a three-phase induction motor.

variable-voltage output without having to go through a DC link. Each phase of the motor has its own dual converter, and obtains power from all three phases of the AC source. The positive half-cycle of current is supplied by the positive converters, and the negative half-cycle by the negative converters. These are indicated in Figure 13.20 as *P* and *N*, respectively.

The output frequency of the cycloconverter is smoothly adjustable from approximately half the input frequency with positive phase sequence, down to zero, and then back up to half the input frequency with negative phase sequence. Thus, given a 60-Hz input, the output frequency can be smoothly adjusted from 30 Hz to 0 Hz to −30 Hz. A three-phase induction motor or synchronous motor, driven by a cycloconverter, can be operated as a reversible adjustable-speed motor with regenerative braking. Controlling the firing angles of the individual converters determines the vo'tage and frequency applied to the motor phases.

The cycloconverter can be designed to handle loads of almost any size and any power factor. One example of the application of a high-power cycloconverter is in the drive system for the *QE 2* cruise ship; cycloconverters are used to control two 59,000-hp, three-phase, adjustable-speed, reversing, synchronous propulsion motors.

13.17 PROGRAMMABLE CONTROLLERS

A programmable controller, also called a programmable logic controller, PC or PLC, is defined by NEMA to be a "digitally operating electronic apparatus that uses a programmable memory for internal storage of instructions for implementing specific functions such as logic, sequencing, timing, counting and arithmetic, to control machines or processes through digital or analog input and output modules."

Programmable controllers were developed in the 1970s to replace hard-wired control panels in the automobile industry, and their success led to their gradual adoption

in virtually all industries with large, complex control systems that must be modified periodically to meet changes in production. The principal advantage of PCs over hard-wired relay panels is the ability to program and reprogram relay logic through a computer terminal, instead of manually wiring, rewiring, or replacing hard-wired panels.

Programmable controllers are designed to withstand the high temperature, humidity, vibration, electrical noise, and power interruptions generally encountered in industrial environments, and are commercially available in small sizes ranging from 50–150 relays to 500–3000 relays in the larger sizes.

The Basic PC

The principal parts of a programmable controller are shown as components of a block diagram in Figure 13.21.

The central processing unit (CPU) contains logic memory, storage memory, power supply, and processor. The CPU receives data from input devices, performs logical decisions based on a stored program, and operates output devices to perform the desired functions.

The solid-state input/output (I/O) interface provides optical isolation to isolate the input and output voltages of field devices from the CPU, and also helps reduce electrical noise. Input field devices include start and stop buttons, limit switches, sensors, and other command devices. Output field devices include such items as motors, magnetic contactors, electric heaters, lights, and electrically operated valves.

The programming keyboard and monitor (TV screen) are used to enter the desired relay logic.

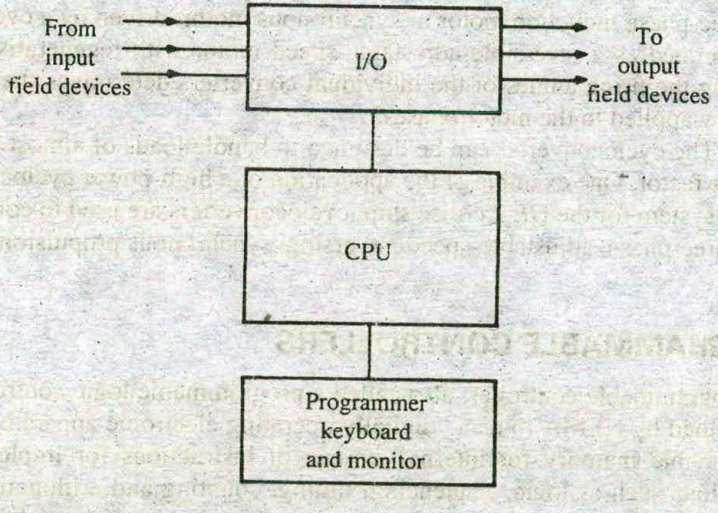


FIGURE 13.21
Basic components of a programmable controller.

Programming a PC

Programming a PC does not require any knowledge of computers, computer language, nor any programming skills. The required control system for a particular application is drawn as a ladder diagram by the design engineer, and the technician or plant engineer types the diagram into the CPU using a special keyboard.

The required number of relay contacts and their configuration, such as normally open, normally closed, series, or parallel, are typed into the computer memory. Then when changes are required, the computer logic can be easily reconfigured from the keyboard; contacts can be added, erased, reconnected, etc. The number of contacts associated with a specific relay coil is limited only by the available memory.

When in operation, a PC scans the programmed logic, starting from the left side of the top rung of the ladder diagram and ending at the right side of the bottom rung. When the last line is scanned, the process repeats, continuing from the time the PC is switched on to the time it is switched off.

For detailed descriptions, diagrams, and photographs of PCs, their mode of operation, and programming techniques, see References **[1],[8],[9]**.

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REVIEW QUESTIONS

1. Explain how a magnetic blow-out coil helps extinguish the arc when the contactor opens.
2. Explain how a shading coil in an AC contactor reduces chatter.
3. Explain the operation of a bimetallic type of motor-overload relay and state how it is connected in the control circuit.
4. What protection, other than motor-overload protection, does a thermal-overload relay provide?
5. Referring to the curves in Figure 13.3(c), if the motor load is such as to cause the current to be 200 percent rated heater current, determine (a) longest time that it will take for the relay to trip; (b) minimum time delay required for cooling before the relay can be reset.
6. What devices are used to protect motor-branch circuits from short circuits or grounds?
7. What type of motor-overload relay is used to protect motors that are subject to jamming? Explain how the relay works.
8. Describe the two general classifications of motor-controller diagrams and state the purpose of each.
9. Sketch a simple control circuit using undervoltage release. What is the characteristic behavior of this type of circuit and where would it be applied?
10. Sketch a simple control circuit using undervoltage protection. What is the characteristic behavior of this type of circuit and where would it be applied?
11. Sketch a full-voltage reversing starter for a three-phase motor. Assume undervoltage protection is required.
12. Explain how the flux-decay timing contactor obtains its time delay.
13. Describe the operation of a cemf starter. What advantage does it have over a definite-time starter?
14. What is the purpose of a field-accelerating relay? Explain how it works.
15. Explain the use of a field-removal relay in a dynamic-braking circuit.
16. What are the advantages of a solid-state starter over a magnetic starter?
17. What are the necessary conditions for switching a thyristor to the on state?
18. What two methods can be used to switch a conducting SCR to the off state?
19. Define commutation in terms of thyristor operation. What is natural commutation?
20. What is a cycloconverter? State an application and explain how it works.
21. What is a programmable controller and in what way does it differ significantly from a magnetic controller?
22. List the principal components of a programmable controller and state their function.