$$P_F = (5\ \text{A})^2(50\ \Omega) = 1250\ \text{W}$$

The brush losses at full load are given by

$$P_{\text{brush}} = V_{\text{BD}} I_A = (2\ \text{V})(170\ \text{A}) = 340\ \text{W}$$

The rotational losses at full load are essentially equivalent to the rotational losses at no load, since the no-load and full-load speeds of the motor do not differ too greatly. These losses may be ascertained by determining the input power to the armature circuit at no load and assuming that the armature copper and brush drop losses are negligible, meaning that the no-load armature input power is equal to the rotational losses:

$$P_{\text{tot}} = P_{\text{core}} + P_{\text{mech}} = (240\ \text{V})(13.2\ \text{A}) = 3168\ \text{W}$$

(a) The input power of this motor at the rated load is given by

$$P_{\text{in}} = V_T I_L = (250\ \text{V})(175\ \text{A}) = 43{,}750\ \text{W}$$

Its output power is given by

$$\begin{aligned} P_{\text{out}} &= P_{\text{in}} - P_{\text{brush}} - P_{\text{cu}} - P_{\text{core}} - P_{\text{mech}} - P_{\text{stray}} \\ &= 43{,}750\ \text{W} - 340\ \text{W} - 1734\ \text{W} - 1250\ \text{W} - 3168\ \text{W} - (0.01)(43{,}750\ \text{W}) \\ &= 36{,}820\ \text{W} \end{aligned}$$

where the stray losses are taken to be 1 percent of the input power.

(b) The efficiency of this motor at full load is

$$\begin{aligned} \eta &= \frac{P_{\text{out}}}{P_{\text{out}}} \times 100\% \\ &= \frac{36{,}820\ \text{W}}{43{,}750\ \text{W}} \times 100\% = 84.2\% \end{aligned}$$

9.11 INTRODUCTION TO DC GENERATORS

DC generators are dc machines used as generators. As previously pointed out, there is no real difference between a generator and a motor except for the direction of power flow. There are five major types of dc generators, classified according to the manner in which their field flux is produced:

1. *Separately excited generator.* In a separately excited generator, the field flux is derived from a separate power source independent of the generator itself.
2. *Shunt generator.* In a shunt generator, the field flux is derived by connecting the field circuit directly across the terminals of the generator.
3. *Series generator.* In a series generator, the field flux is produced by connecting the field circuit in series with the armature of the generator.
4. *Cumulatively compounded generator.* In a cumulatively compounded generator, both a shunt and a series field are present, and their effects are additive.
5. *Differentially compounded generator.* In a differentially compounded generator, both a shunt and a series field are present, but their effects are subtractive.

These various types of dc generators differ in their terminal (voltage–current) characteristics, and therefore in the applications to which they are suited.

FIGURE 9–41
The first practical dc generator. This is an exact duplicate of the "long-legged Mary Ann," Thomas Edison's first commercial dc generator, which was built in 1879. It was rated at 5 kW, 100 V, and 1200 r/min. (*Courtesy of General Electric Company.*)

DC generators are compared by their voltages, power ratings, efficiencies, and voltage regulations. *Voltage regulation* (VR) is defined by the equation

$$\boxed{\mathrm{VR} = \frac{V_{\mathrm{nl}} - V_{\mathrm{fl}}}{V_{\mathrm{fl}}} \times 100\%} \qquad (9\text{–}39)$$

where V_{nl} is the no-load terminal voltage of the generator and V_{fl} is the full-load terminal voltage of the generator. It is a rough measure of the shape of the generator's voltage–current characteristic—a positive voltage regulation means a drooping characteristic, and a negative voltage regulation means a rising characteristic.

All generators are driven by a source of mechanical power, which is usually called the *prime mover* of the generator. A prime mover for a dc generator may be a steam turbine, a diesel engine, or even an electric motor. Since the speed of the prime mover affects the output voltage of a generator, and since prime movers can vary widely in their speed characteristics, it is customary to compare the voltage regulation and output characteristics of different generators, *assuming constant-speed prime movers*. Throughout this chapter, a generator's speed will be assumed to be constant unless a specific statement is made to the contrary.

DC generators are quite rare in modern power systems. Even dc power systems such as those in automobiles now use ac generators plus rectifiers to produce dc power.

The equivalent circuit of a dc generator is shown in Figure 9–42, and a simplified version of the equivalent circuit is shown in Figure 9–43. They look similar to the equivalent circuits of a dc motor, except that the direction of current flow and the brush loss are reversed.

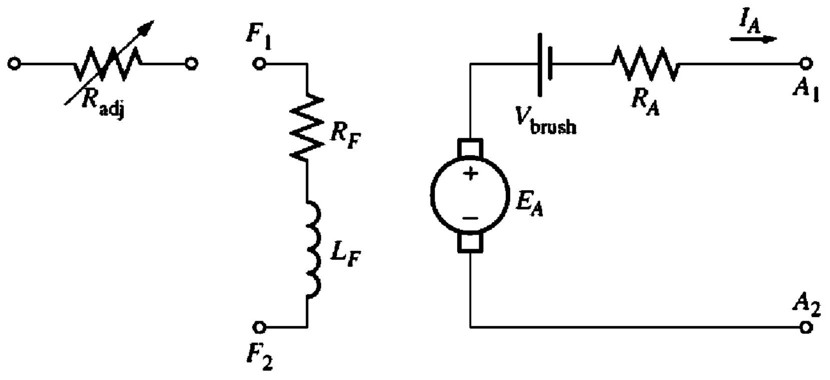


FIGURE 9–42
The equivalent circuit of a dc generator.

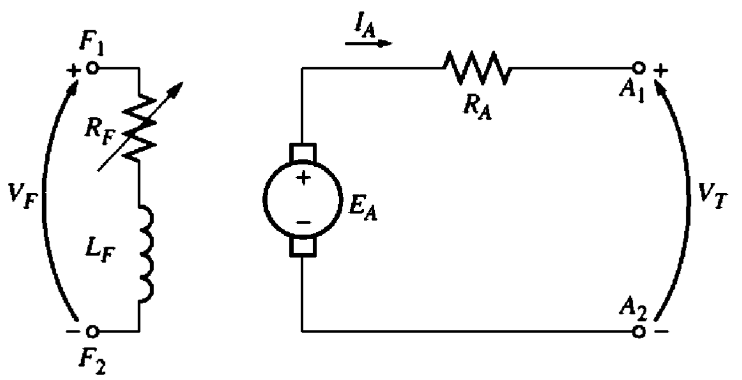


FIGURE 9–43
A simplified equivalent circuit of a dc generator, with R_F combining the resistances of the field coils and the variable control resistor.

9.12 THE SEPARATELY EXCITED GENERATOR

A separately excited dc generator is a generator whose field current is supplied by a separate external dc voltage source. The equivalent circuit of such a machine is shown in Figure 9–44. In this circuit, the voltage V_T represents the actual voltage measured at the terminals of the generator, and the current I_L represents the current flowing in the lines connected to the terminals. The internal generated voltage is E_A, and the armature current is I_A. It is clear that the armature current is equal to the line current in a separately excited generator:

$$I_A = I_L \tag{9–40}$$

The Terminal Characteristic of a Separately Excited DC Generator

The *terminal characteristic* of a device is a plot of the output quantities of the device versus each other. For a dc generator, the output quantities are its terminal voltage and line current. The terminal characteristic of a separately excited generator is

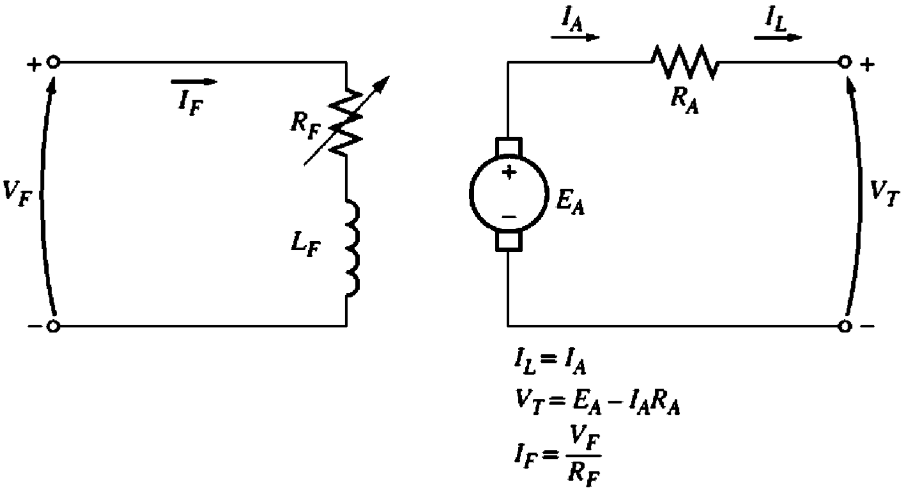


FIGURE 9–44
A separately excited dc generator.

thus a plot of V_T versus I_L for a constant speed ω. By Kirchhoff's voltage law, the terminal voltage is

$$\boxed{V_T = E_A - I_A R_A} \tag{9–41}$$

Since the internal generated voltage is independent of I_A, the terminal characteristic of the separately excited generator is a straight line, as shown in Figure 9–45a.

What happens in a generator of this sort when the load is increased? When the load supplied by the generator is increased, I_L (and therefore I_A) increases. As the armature current increases, the $I_A R_A$ drop increases, so the terminal voltage of the generator falls.

This terminal characteristic is not always entirely accurate. In generators without compensating windings, an increase in I_A causes an increase in armature reaction, and armature reaction causes flux weakening. This flux weakening causes a decrease in $E_A = K\phi\downarrow\omega$ which further decreases the terminal voltage of the generator. The resulting terminal characteristic is shown in Figure 9–45b. In all future plots, the generators will be assumed to have compensating windings unless stated otherwise. However, it is important to realize that armature reaction can modify the characteristics if compensating windings are not present.

Control of Terminal Voltage

The terminal voltage of a separately excited dc generator can be controlled by changing the internal generated voltage E_A of the machine. By Kirchhoff's voltage law $V_T = E_A - I_A R_A$, so if E_A increases, V_T will increase, and if E_A decreases, V_T will decrease. Since the internal generated voltage E_A is given by the equation $E_A = K\phi\omega$, there are two possible ways to control the voltage of this generator:

1. *Change the speed of rotation.* If ω increases, then $E_A = K\phi\omega\uparrow$ increases, so $V_T = E_A\uparrow - I_A R_A$ increases too.

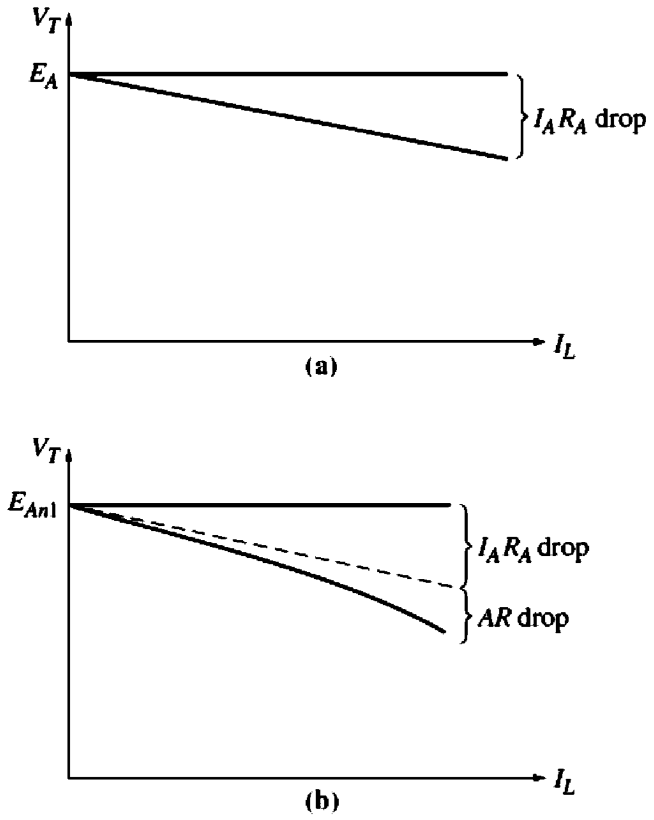


FIGURE 9–45
The terminal characteristic of a separately excited dc generator (a) with and (b) without compensating windings.

2. *Change the field current.* If R_F is decreased, then the field current increases ($I_F = V_F / R_F\downarrow$). Therefore, the flux ϕ in the machine increases. As the flux rises, $E_A = K\phi\uparrow\omega$ must rise too, so $V_T = E_A\uparrow - I_A R_A$ increases.

In many applications, the speed range of the prime mover is quite limited, so the terminal voltage is most commonly controlled by changing the field current. A separately excited generator driving a resistive load is shown in Figure 9–46a. Figure 9–46b shows the effect of a decrease in field resistance on the terminal voltage of the generator when it is operating under a load.

Nonlinear Analysis of a Separately Excited DC Generator

Because the internal generated voltage of a generator is a nonlinear function of its magnetomotive force, it is not possible to calculate simply the value of E_A to be expected from a given field current. The magnetization curve of the generator must be used to accurately calculate its output voltage for a given input voltage.

In addition, if a machine has armature reaction, its flux will be reduced with each increase in load, causing E_A to decrease. The only way to accurately determine the output voltage in a machine with armature reaction is to use graphical analysis.

The total magnetomotive force in a separately excited generator is the field circuit magnetomotive force less the magnetomotive force due to armature reaction (AR):

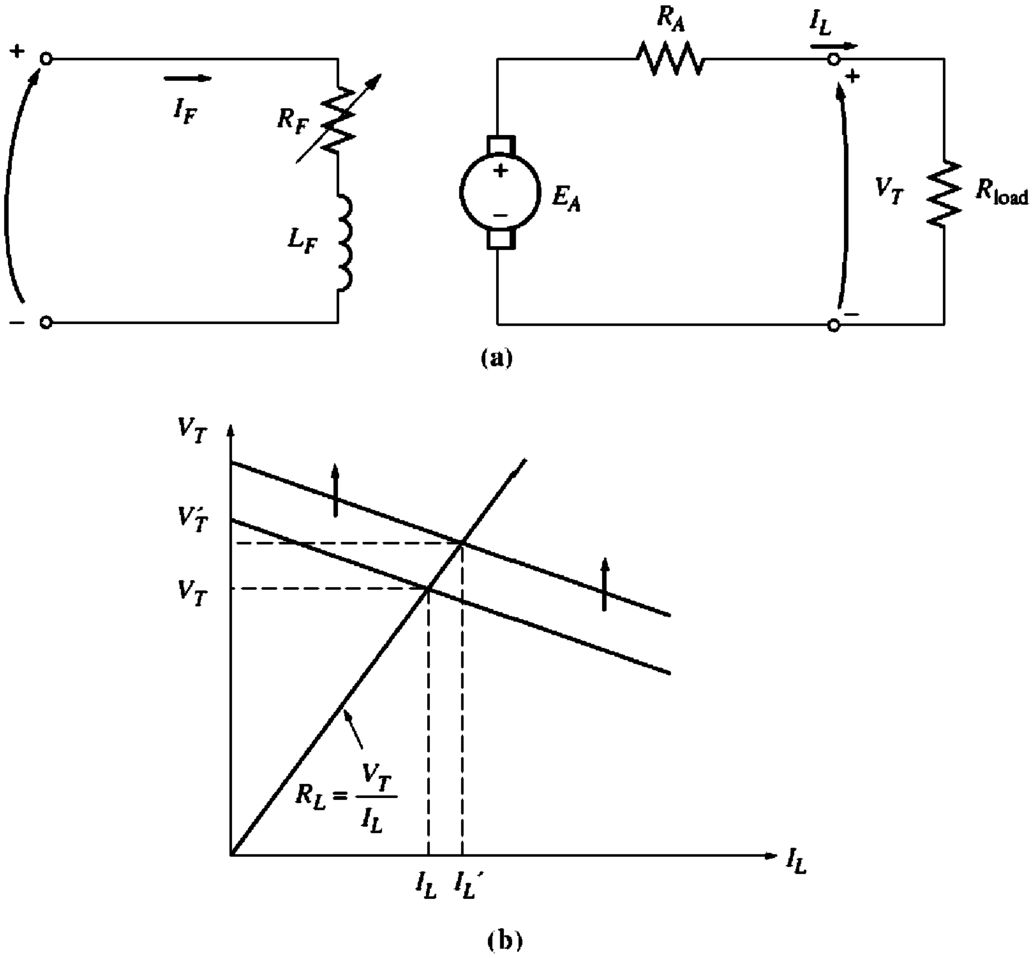


FIGURE 9–46
(a) A separately excited dc generator with a resistive load. (b) The effect of a decrease in field resistance on the output voltage of the generator.

$$\mathscr{F}_{net} = N_F I_F - \mathscr{F}_{AR} \tag{9–42}$$

As with dc motors, it is customary to define an ***equivalent field current*** that would produce the same output voltage as the combination of all the magnetomotive forces in the machine. The resulting voltage E_{A0} can then be determined by locating that equivalent field current on the magnetization curve. The equivalent field current of a separately excited dc generator is given by

$$I_F^* = I_F - \frac{\mathscr{F}_{AR}}{N_F} \tag{9–43}$$

Also, the difference between the speed of the magnetization curve and the real speed of the generator must be taken into account using Equation (9–13):

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \tag{9–13}$$

The following example illustrates the analysis of a separately excited dc generator.

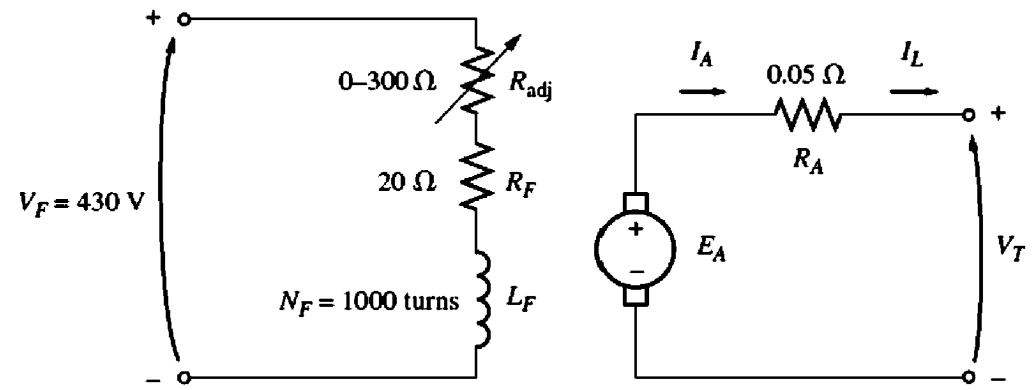


FIGURE 9–47
The separately excited dc generator in Example 9–9.

Example 9–9. A separately excited dc generator is rated at 172 kW, 430 V, 400 A, and 1800 r/min. It is shown in Figure 9–47, and its magnetization curve is shown in Figure 9–48. This machine has the following characteristics:

$$R_A = 0.05\ \Omega \qquad V_F = 430\ \text{V}$$
$$R_F = 20\ \Omega \qquad N_F = 1000 \text{ turns per pole}$$
$$R_{adj} = 0 \text{ to } 300\ \Omega$$

(*a*) If the variable resistor R_{adj} in this generator's field circuit is adjusted to 63 Ω and the generator's prime mover is driving it at 1600 r/min, what is this generator's no-load terminal voltage?

(*b*) What would its voltage be if a 360-A load were connected to its terminals? Assume that the generator has compensating windings.

(*c*) What would its voltage be if a 360-A load were connected to its terminals but the generator does not have compensating windings? Assume that its armature reaction at this load is 450 A • turns.

(*d*) What adjustment could be made to the generator to restore its terminal voltage to the value found in part *a*?

(*e*) How much field current would be needed to restore the terminal voltage to its no-load value? (Assume that the machine has compensating windings.) What is the required value for the resistor R_{adj} to accomplish this?

Solution

(*a*) If the generator's total field circuit resistance is

$$R_F + R_{adj} = 83\ \Omega$$

then the field current in the machine is

$$I_F = \frac{V_F}{R_F} = \frac{430\ \text{V}}{83\ \Omega} = 5.2\ \text{A}$$

From the machine's magnetization curve, this much current would produce a voltage $E_{A0} = 430$ V at a speed of 1800 r/min. Since this generator is actually turning at $n_m = 1600$ r/min, its internal generated voltage E_A will be

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \tag{9–13}$$

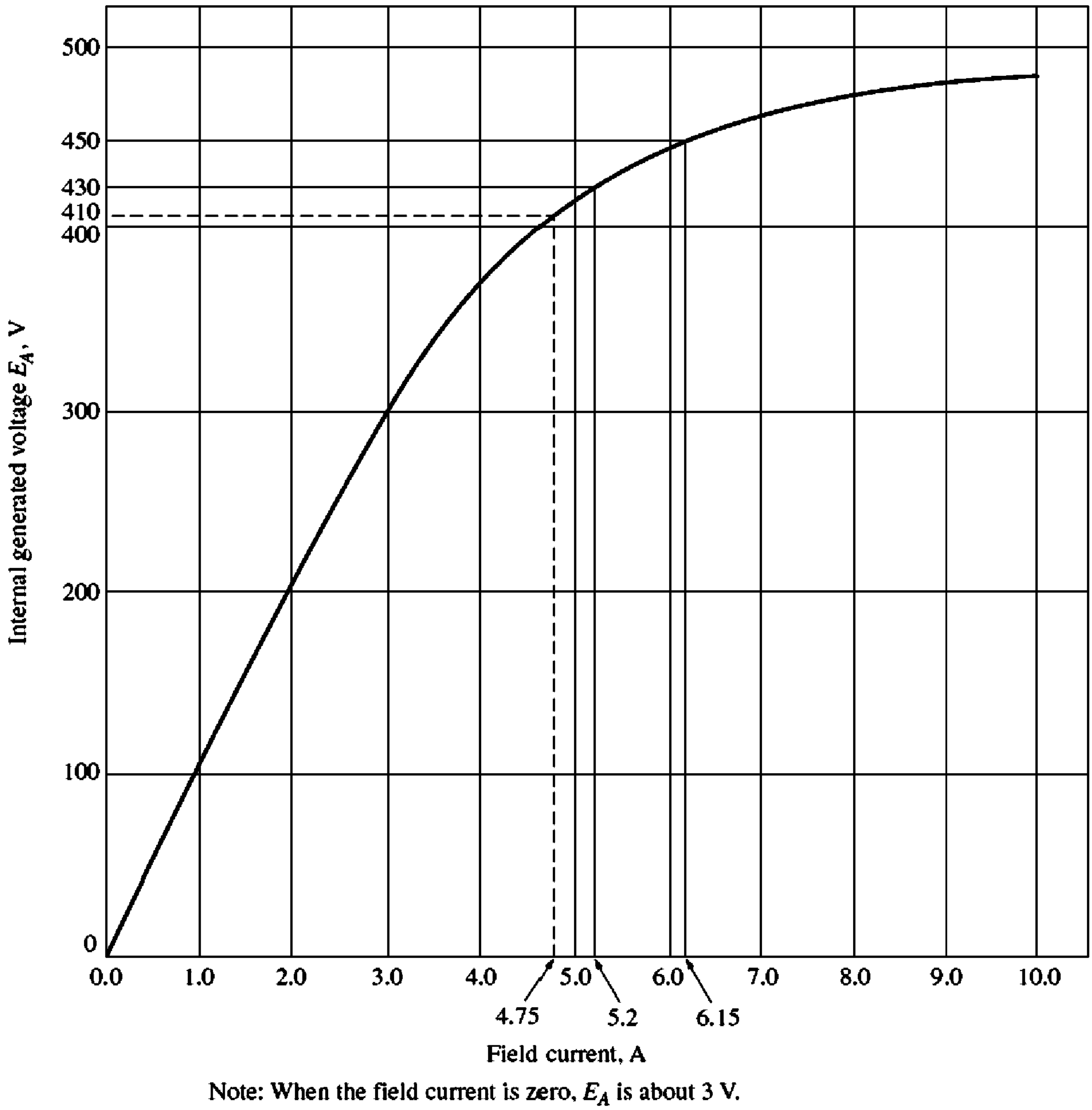


FIGURE 9–48
The magnetization curve for the generator in Example 9–9.

$$E_A = \frac{1600 \text{ r/min}}{1800 \text{ r/min}} 430 \text{ V} = 382 \text{ V}$$

Since $V_T = E_A$ at no-load conditions, the output voltage of the generator is $V_T =$ 382 V.

(*b*) If a 360-A load were connected to this generator's terminals, the terminal voltage of the generator would be

$$V_T = E_A - I_A R_A = 382 \text{ V} - (360 \text{ A})(0.05\ \Omega) = 364 \text{ V}$$

(*c*) If a 360-A load were connected to this generator's terminals and the generator had 450 A • turns of armature reaction, the effective field current would be

$$I_F^* = I_F - \frac{\mathcal{F}_{AR}}{N_F} = 5.2 \text{ A} - \frac{450 \text{ A} \bullet \text{turns}}{1000 \text{ turns}} = 4.75 \text{ A}$$

From the magnetization curve, $E_{A0} = 410$ V, so the internal generated voltage at 1600 r/min would be

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \tag{9–13}$$

$$E_A = \frac{1600 \text{ r/min}}{1800 \text{ r/min}} 410 \text{ V} = 364 \text{ V}$$

Therefore, the terminal voltage of the generator would be

$$V_T = E_A - I_A R_A = 364 \text{ V} - (360 \text{ A})(0.05\ \Omega) = 346 \text{ V}$$

It is lower than before due to the armature reaction.

(*d*) The voltage at the terminals of the generator has fallen, so to restore it to its original value, the voltage of the generator must be increased. This requires an increase in E_A, which implies that R_{adj} must be decreased to increase the field current of the generator.

(*e*) For the terminal voltage to go back up to 382 V, the required value of E_A is

$$E_A = V_T + I_A R_A = 382 \text{ V} + (360 \text{ A})(0.05\ \Omega) = 400 \text{ V}$$

To get a voltage E_A of 400 V at $n_m = 1600$ r/min, the equivalent voltage at 1800 r/min would be

$$\frac{E_A}{E_{A0}} = \frac{n}{n_0} \tag{9–13}$$

$$E_{A0} = \frac{1800 \text{ r/min}}{1600 \text{ r/min}} 400 \text{ V} = 450 \text{ V}$$

From the magnetization curve, this voltage would require a field current of $I_F = 6.15$ A. The field circuit resistance would have to be

$$R_F + R_{adj} = \frac{V_F}{I_F}$$

$$20\ \Omega + R_{adj} = \frac{430 \text{ V}}{6.15 \text{ A}} = 69.9\ \Omega$$

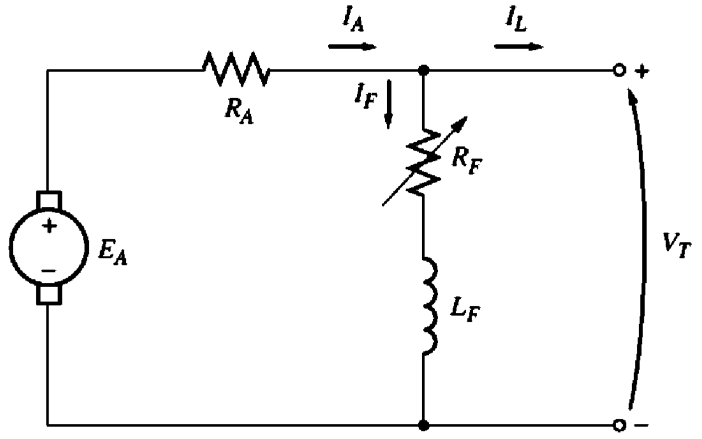
$$R_{adj} = 49.9\ \Omega \approx 50\ \Omega$$

Notice that, for the same field current and load current, the generator with armature reaction had a lower output voltage than the generator without armature reaction. The armature reaction in this generator is exaggerated to illustrate its effects—it is a good deal smaller in well-designed modern machines.

9.13 THE SHUNT DC GENERATOR

A shunt dc generator is a dc generator that supplies its own field current by having its field connected directly across the terminals of the machine. The equivalent circuit of a shunt dc generator is shown in Figure 9–49. In this circuit, the armature current of the machine supplies both the field circuit and the load attached to the machine:

$$\boxed{I_A = I_F + I_L} \tag{9–44}$$



$$I_A = I_F + I_L$$
$$V_T = E_A - I_A R_A$$
$$I_F = \frac{V_T}{R_F}$$

FIGURE 9–49
The equivalent circuit of a shunt dc generator.

The Kirchhoff's voltage law equation for the armature circuit of this machine is

$$\boxed{V_T = E_A - I_A R_A} \qquad (9\text{–}45)$$

This type of generator has a distinct advantage over the separately excited dc generator in that no external power supply is required for the field circuit. But that leaves an important question unanswered: If the generator supplies its own field current, how does it get the initial field flux to start when it is first turned on?

Voltage Buildup in a Shunt Generator

Assume that the generator in Figure 9–49 has no load connected to it and that the prime mover starts to turn the shaft of the generator. How does an initial voltage appear at the terminals of the machine?

The voltage buildup in a dc generator depends on the presence of a *residual flux* in the poles of the generator. When a generator first starts to turn, an internal voltage will be generated which is given by

$$E_A = K\phi_{\text{res}}\omega$$

This voltage appears at the terminals of the generator (it may only be a volt or two). But when that voltage appears at the terminals, it causes a current to flow in the generator's field coil ($I_F = V_T\uparrow/R_F$). This field current produces a magnetomotive force in the poles, which increases the flux in them. The increase in flux causes an increase in $E_A = K\phi\uparrow\omega$, which increases the terminal voltage V_T. When V_T rises, I_F increases further, increasing the flux ϕ more, which increases E_A, etc.

This voltage buildup behavior is shown in Figure 9–50. Notice that it is the effect of magnetic saturation in the pole faces which eventually limits the terminal voltage of the generator.

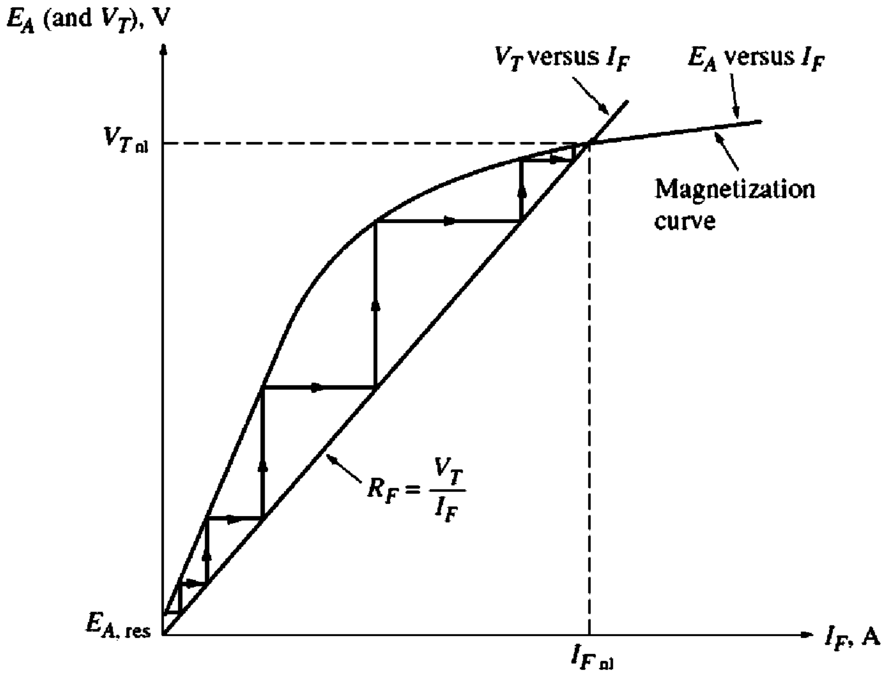


FIGURE 9–50
Voltage buildup on starting in a shunt dc generator.

Figure 9–50 shows the voltage buildup as though it occurred in discrete steps. These steps are drawn in to make obvious the positive feedback between the generator's internal voltage and its field current. In a real generator, the voltage does not build up in discrete steps: Instead both E_A and I_F increase simultaneously until steady-state conditions are reached.

What if a shunt generator is started and no voltage builds up? What could be wrong? There are several possible causes for the voltage to fail to build up during starting. Among them are

1. *There may be no residual magnetic flux* in the generator to start the process going. If the residual flux $\phi_{res} = 0$, then $E_A = 0$, and the voltage never builds up. If this problem occurs, disconnect the field from the armature circuit and connect it directly to an external dc source such as a battery. The current flow from this external dc source will leave a residual flux in the poles, which will then allow normal starting. This procedure is known as "flashing the field."
2. *The direction of rotation of the generator may have been reversed,* or the connections of the field may have been reversed. In either case, the residual flux produces an internal generated voltage E_A. The voltage E_A produces a field current which produces a flux *opposing* the residual flux, instead of adding to it. Under these circumstances, the flux actually *decreases* below ϕ_{res} and no voltage can ever build up.

   If this problem occurs, it can be fixed by reversing the direction of rotation, by reversing the field connections, or by flashing the field with the opposite magnetic polarity.

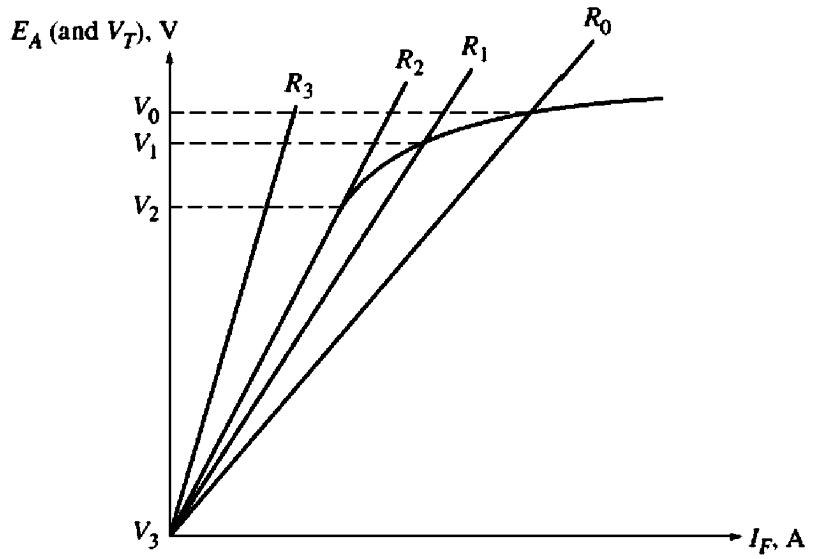


FIGURE 9–51
The effect of shunt field resistance on no-load terminal voltage in a dc generator. If $R_F > R_2$ (the critical resistance), then the generator's voltage will never build up.

3. *The field resistance may be adjusted to a value greater than the critical resistance.* To understand this problem, refer to Figure 9–51. Normally, the shunt generator will build up to the point where the magnetization curve intersects the field resistance line. If the field resistance has the value shown at R_2 in the figure, its line is nearly parallel to the magnetization curve. At that point, the voltage of the generator can fluctuate very widely with only tiny changes in R_F or I_A. This value of the resistance is called the *critical resistance*. If R_F exceeds the critical resistance (as at R_3 in the figure), then the steady-state operating voltage is essentially at the residual level, and it never builds up. The solution to this problem is to reduce R_F.

Since the voltage of the magnetization curve varies as a function of shaft speed, the critical resistance also varies with speed. In general, the lower the shaft speed, the lower the critical resistance.

The Terminal Characteristic of a Shunt DC Generator

The terminal characteristic of a shunt dc generator differs from that of a separately excited dc generator, because the amount of field current in the machine depends on its terminal voltage. To understand the terminal characteristic of a shunt generator, start with the machine unloaded and add loads, observing what happens.

As the load on the generator is increased, I_L increases and so $I_A = I_F + I_L \uparrow$ also increases. An increase in I_A increases the armature resistance voltage drop $I_A R_A$, causing $V_T = E_A - I_A \uparrow R_A$ to decrease. This is precisely the same behavior observed in a separately excited generator. However, when V_T decreases, the field current in the machine decreases with it. This causes the flux in the machine to

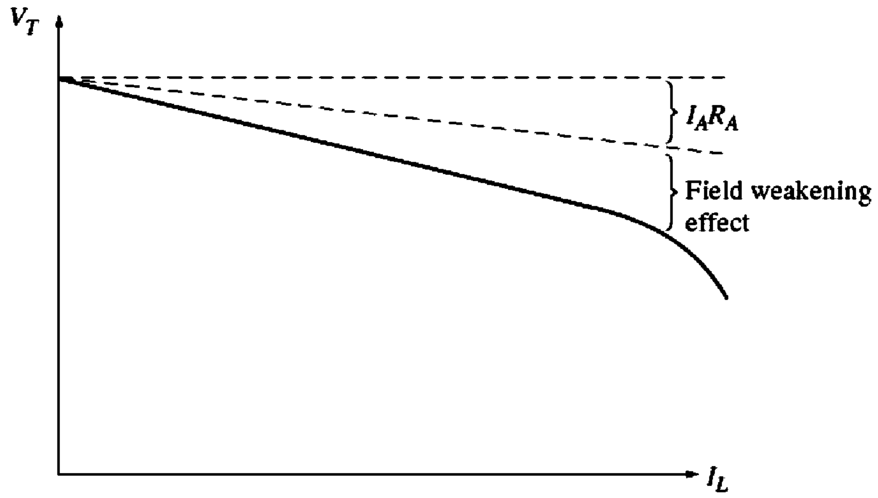


FIGURE 9–52
The terminal characteristic of a shunt dc generator.

decrease, decreasing E_A. Decreasing E_A causes a further decrease in the terminal voltage $V_T = E_A\downarrow - I_A R_A$. The resulting terminal characteristic is shown in Figure 9–52. Notice that the voltage drop-off is steeper than just the $I_A R_A$ drop in a separately excited generator. In other words, the voltage regulation of this generator is worse than the voltage regulation of the same piece of equipment connected separately excited.

Voltage Control for a Shunt DC Generator

As with the separately excited generator, there are two ways to control the voltage of a shunt generator:

1. Change the shaft speed ω_m of the generator.
2. Change the field resistor of the generator, thus changing the field current.

Changing the field resistor is the principal method used to control terminal voltage in real shunt generators. If the field resistor R_F is decreased, then the field current $I_F = V_T/R_F\downarrow$ increases. When I_F increases, the machine's flux ϕ increases, causing the internal generated voltage E_A to increase. The increase in E_A causes the terminal voltage of the generator to increase as well.

The Analysis of Shunt DC Generators

The analysis of a shunt dc generator is somewhat more complicated than the analysis of a separately excited generator, because the field current in the machine depends directly on the machine's own output voltage. First the analysis of shunt generators is studied for machines with no armature reaction, and afterward the effects are armature reaction are included.

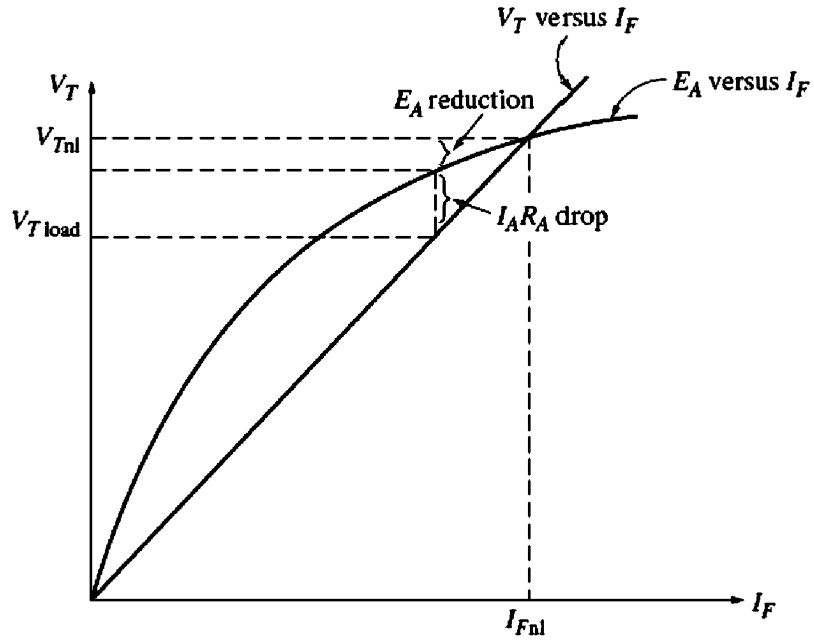


FIGURE 9–53
Graphical analysis of a shunt dc generator with compensating windings.

Figure 9–53 shows a magnetization curve for a shunt dc generator drawn at the actual operating speed of the machine. The field resistance R_F, which is just equal to V_T/I_F, is shown by a straight line laid over the magnetization curve. *At no load*, $V_T = E_A$ and the generator operates at the voltage where the magnetization curve intersects the field resistance line.

The key to understanding the graphical analysis of shunt generators is to remember Kirchhoff's voltage law (KVL):

$$V_T = E_A - I_AR_A \tag{9–45}$$

or

$$\boxed{E_A - V_T = I_AR_A} \tag{9–46}$$

The difference between the internal generated voltage and the terminal voltage is just the I_AR_A drop in the machine. The line of all possible values of E_A is the magnetization curve, and the line of all possible terminal voltages is the resistor line ($I_F = V_T/R_F$). Therefore, to find the terminal voltage for a given load, just determine the I_AR_A drop and locate the place on the graph where that drop fits *exactly* between the E_A line and the V_T line. There are at most two places on the curve where the I_AR_A drop will fit exactly. If there are two possible positions, the one nearer the no-load voltage will represent a normal operating point.

A detailed plot showing several different points on a shunt generator's characteristic is shown in Figure 9–54. Note the dashed line in Figure 9–54b. This line is the terminal characteristic when the load is being reduced. The reason that it does not coincide with the line of increasing load is the hysteresis in the stator poles of the generator.

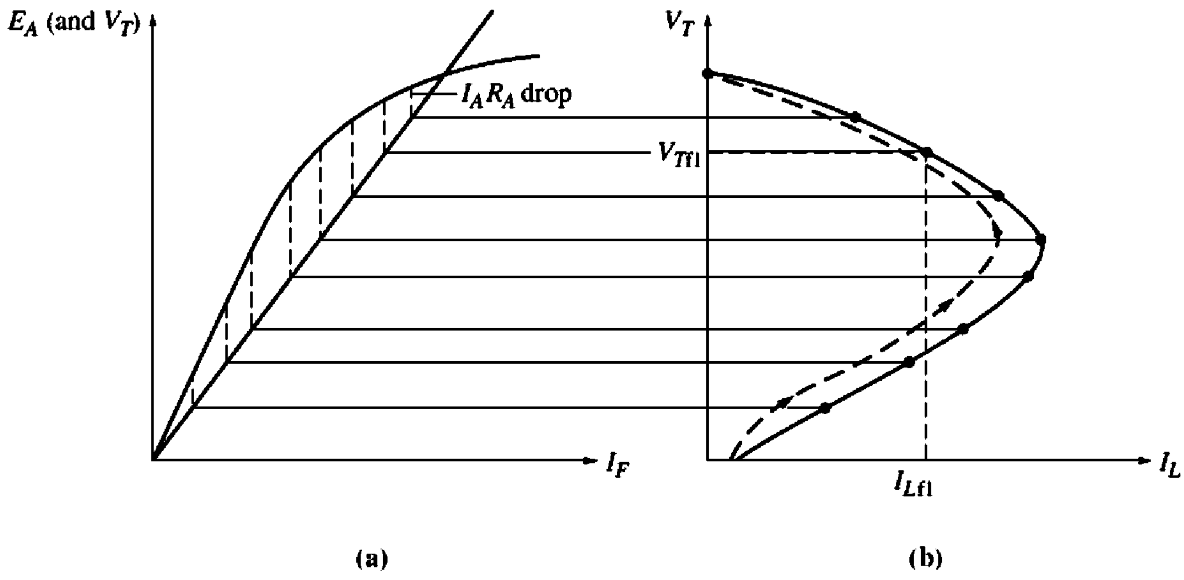


FIGURE 9–54
Graphical derivation of the terminal characteristic of a shunt dc generator.

If armature reaction is present in a shunt generator, this process becomes a little more complicated. The armature reaction produces a demagnetizing magnetomotive force in the generator at the same time that the $I_A R_A$ drop occurs in the machine.

To analyze a generator with armature reaction present, assume that its armature current is known. Then the resistive voltage drop $I_A R_A$ is known, and the demagnetizing magnetomotive force of the armature current is known. The terminal voltage of this generator must be large enough to supply the generator's flux *after the demagnetizing effects of armature reaction have been subtracted.* To meet this requirement both the armature reaction magnetomotive force and the $I_A R_A$ drop must fit between the E_A line and the V_T line. To determine the output voltage for a given magnetomotive force, simply locate the place under the magnetization curve where the triangle formed by the armature reaction and $I_A R_A$ effects *exactly fits* between the line of possible V_T values and the line of possible E_A values (see Figure 9–55).

9.14 THE SERIES DC GENERATOR

A series dc generator is a generator whose field is connected in series with its armature. Since the armature has a *much* higher current than a shunt field, the series field in a generator of this sort will have only a very few turns of wire, and the wire used will be much thicker than the wire in a shunt field. Because magnetomotive force is given by the equation $\mathcal{F} = NI$, exactly the same magnetomotive force can be produced from a few turns with high current as can be produced from many turns with low current. Since the full-load current flows through it, a series field is designed to have the lowest possible resistance. The equivalent circuit of a series dc generator is shown in Figure 9–56. Here, the armature current, field

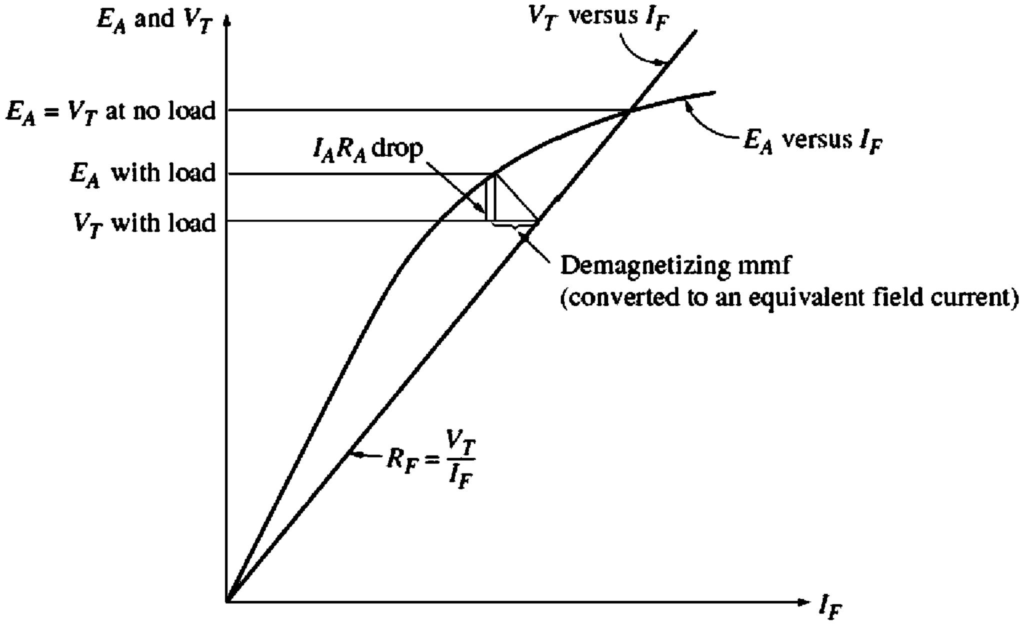


FIGURE 9–55
Graphical analysis of a shunt dc generator with armature reaction.

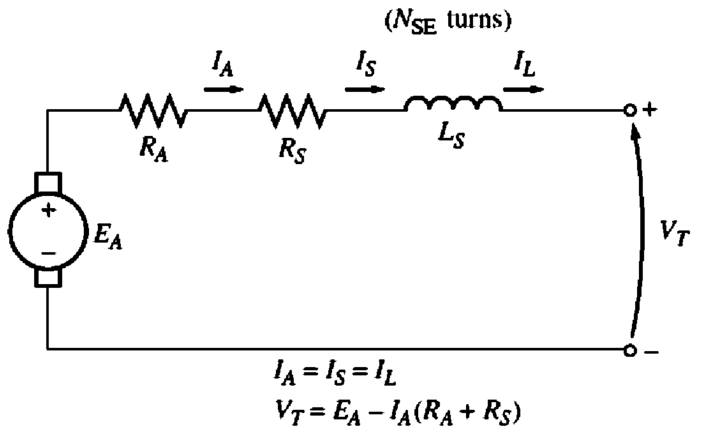


FIGURE 9–56
The equivalent circuit of a series dc generator.

current, and line current all have the same value. The Kirchhoff's voltage law equation for this machine is

$$\boxed{V_T = E_A - I_A(R_A + R_S)} \tag{9–47}$$

The Terminal Characteristic of a Series Generator

The magnetization curve of a series dc generator looks very much like the magnetization curve of any other generator. At no load, however, there is no field current, so V_T is reduced to a small level given by the residual flux in the machine. As the load increases, the field current rises, so E_A rises rapidly. The $I_A(R_A + R_S)$ drop goes up too, but at first the increase in E_A goes up more rapidly than the $I_A(R_A + R_S)$ drop rises, so V_T increases. After a while, the machine approaches saturation, and E_A

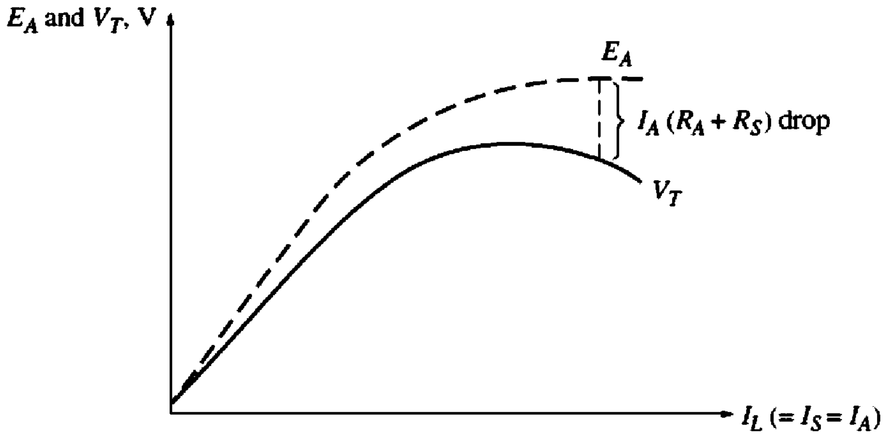


FIGURE 9–57
Derivation of the terminal characteristic for a series dc generator.

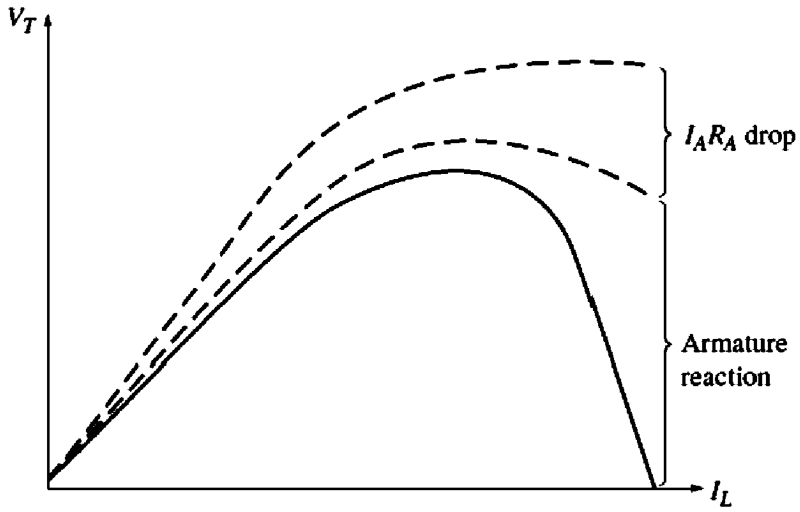


FIGURE 9–58
A series generator terminal characteristic with large armature reaction effects, suitable for electric welders.

becomes almost constant. At that point, the resistive drop is the predominant effect, and V_T starts to fall.

This type of characteristic is shown in Figure 9–57. It is obvious that this machine would make a bad constant-voltage source. In fact, its voltage regulation is a large negative number.

Series generators are used only in a few specialized applications, where the steep voltage characteristic of the device can be exploited. One such application is arc welding. Series generators used in arc welding are deliberately designed to have a large armature reaction, which gives them a terminal characteristic like the one shown in Figure 9–58. Notice that when the welding electrodes make contact with each other before welding commences, a very large current flows. As the operator separates the welding electrodes, there is a very steep rise in the generator's voltage, while the current remains high. This voltage ensures that a welding arc is maintained through the air between the electrodes.