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Compound Motors

by Thomas E. Kissell

Industrial Electronics, Second Edition, Prentice Hall PTR

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The DC compound motor is a combination of the series motor and the shunt motor. It has a series field winding that is connected in series with the armature and a shunt field that is in parallel with the armature. The combination of series and shunt winding allows the motor to have the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor. Figure 12-17 shows a diagram of the compound motor. Several versions of the compound motor are also shown in this diagram.

Table of Contents:

- Cumulative Compound Motors
- Differential Compound Motors
- Compound Interpole Motors
- Reversing the Rotation
- Controlling the Speed

Cumulative Compound Motors

Figure 12-17a shows a diagram of the cumulative compound motor. It is so called because the shunt field is connected so that its coils are aiding the magnetic fields of the series field and armature. The shunt winding can be wired as a *long shunt* or as a *short shunt*. Figure 12-17a and Fig. 12-17b show the motor connected as a short shunt where the shunt field is connected in parallel with only the armature. Figure 12-17c shows the motor connected as a long shunt where the shunt field is connected in parallel with both the series field, interpoles, and the armature.

Figure 12-17a also shows the short shunt motor as a cumulative compound motor, which means the polarity of the shunt field matches the polarity of the armature. You can see in this figure that the top of the shunt field is positive polarity and that it is connected to the positive terminal of the armature. In Fig. 12-17b you can see that the shunt field has been reversed so that the negative terminal of the shunt field is now connected to the positive terminal of the armature. This type of motor is called a differential compound because the polarities of the shunt field and the armature are opposite.

The cumulative compound motor is one of the most common DC motors because it provides high starting torque and good speed regulation at high speeds. Since the shunt field is wired with similar polarity in parallel with the magnetic field aiding the series field and armature field, it is called cumulative. When the motor is connected this way, it can start even with a large load and then operate smoothly when the load varies slightly.

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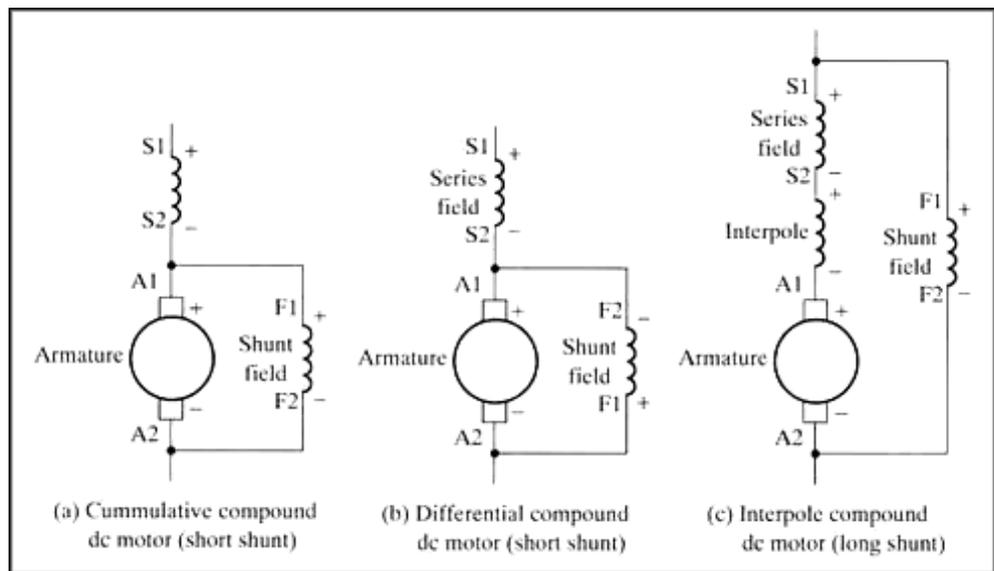


FIGURE 12-17 (a) Diagram of a cumulative compound motor, (b) Diagram of a differential compound motor, (c) Diagram of an interpole compound motor.

You should recall that the shunt motor can provide smooth operation at full speed, but it cannot start with a large load attached, and the series motor can start with a heavy load, but its speed cannot be controlled. The cumulative compound motor takes the best characteristics of both the series motor and shunt motor, which makes it acceptable for most applications.

Differential Compound Motors

Differential compound motors use the same motor and windings as the cumulative compound motor, but they are connected in a slightly different manner to provide slightly different operating speed and torque characteristics. Figure 12-17b shows the diagram for a differential compound motor with the shunt field connected so its polarity is reversed to the polarity of the armature. Since the shunt field is still connected in parallel with only the armature, it is considered a short shunt.

In this diagram you should notice that F1 and F2 are connected in reverse polarity to the armature. In the differential compound motor the shunt field is connected so that its magnetic field opposes the magnetic fields in the armature and series field. When the shunt field's polarity is reversed like this, its field will oppose the other fields and the characteristics of the shunt motor are not as pronounced in this motor. This means that the motor will tend to overspeed when the load is reduced just like a series motor. Its speed will also drop more than the cumulative compound motor when the load increases at full rpm. These two characteristics make the differential motor less desirable than the cumulative motor for most applications.

Compound Interpole Motors

The compound interpole motor is built slightly differently from the cumulative and differential compound motors. This motor has interpoles connected in series with the armature (Fig. 12-17c). The interpoles are connected in series between the armature and series winding. It is physically located beside the series coil in the stator. It is made of wire that is the same gauge as the series winding and it is connected so that its polarity is the same as the series winding pole it is mounted behind. Remember that these motors may have any number of poles to make the field stronger.

The interpole prevents the armature and brushes from arcing due to the buildup of magnetic forces. These forces are created from counter EMF called *armature reaction*. They are so effective that normally all DC compound motors that are larger than 1/2 hp will utilize them. Since the brushes do not arc, they will last longer and the armature will not need to be cut down as often. The interpoles also allow the armature to draw heavier currents and carry larger shaft loads.

When the interpoles are connected, they must be tested carefully to determine their polarity so that it can be matched with the main pole. If the polarity of the interpoles does not match the main pole it is mounted behind, it will cause the motor to overheat and may damage the series winding.

Reversing the Rotation

Each of the compound motors shown in Fig. 12-17 can be reversed by changing the polarity of the armature winding. If the motor has interpoles, the polarity of the interpole must be changed when the armature's polarity is changed. Since the interpole is connected in series with the armature, it should be reversed when the armature is reversed. The interpoles are not shown in the diagram to keep it simplified. The armature winding is always marked as A1 and A2 and these terminals should be connected to the contacts of the reversing motor starter.

Controlling the Speed

The speed of a compound motor can be changed very easily by adjusting the amount of voltage applied to it. In fact, it can be generalized that prior to the late 1970s, any industrial application that required a motor to have a constant speed would be handled by an AC motor, and any application that required the load to be driven at variable speeds would automatically be handled by a DC motor. This statement was true because the speed of a DC motor was easier to change than an AC motor. Since the advent of solid-state components and microprocessor controls, this condition is no longer true. In fact, today a solid-state AC variable-frequency motor drive can vary the speed of an AC motor as easily as that of DC motors. This brings about a condition where you must understand methods of controlling the speed of both AC and DC motors. Information about AC motor speed control is provided in Chapter 11 (see the related links).

Figure 12-18 shows the characteristic curves of the speed versus armature current for the compound motors. From this diagram you can see that the speed of a differential compound motor increases slightly when the motor is drawing the armature highest current. The increase in speed occurs because the extra current in the differential winding causes the magnetic field in the motor to weaken slightly because the magnetic field in the differential winding opposes the magnetic in series field. As you learned earlier in the speed control of shunt motors, the speed of the motor will increase if the magnetic field is weakened.

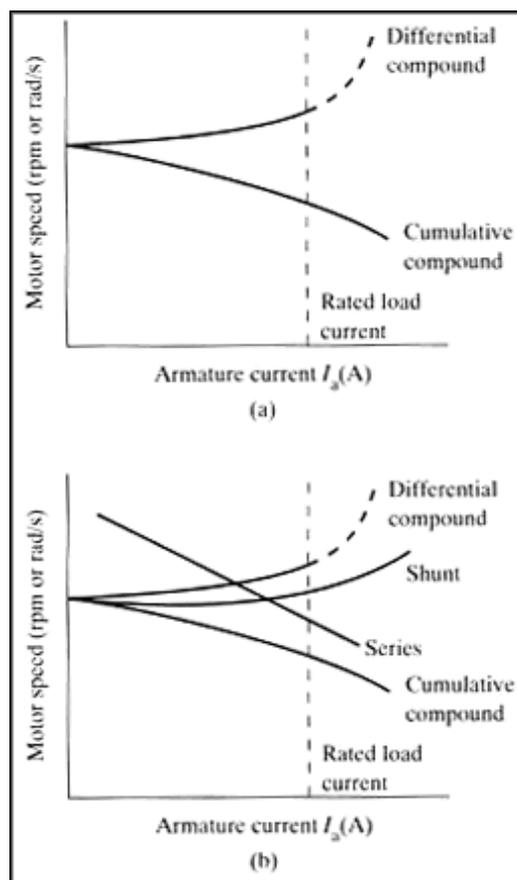


FIGURE 12-18 (a) Characteristic curve of armature current versus speed for the differential compound motor and cumulative compound motor, (b) Composite of the characteristic curves for all of the DC motors.

Figure 12-18 also shows the characteristic curve for the cumulative compound motor. This curve shows that the speed of the cumulative compound motor decreases slightly because

the field is increased, which slows the motor because the magnetic field in the shunt winding aids the magnetic field of the series field.

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DC Motor Calculations, part 1

by Theodore Wildi

Electrical Machines, Drives, and Power Systems, Fourth Edition, Prentice Hall PTR

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Now that we have a good understanding of dc generators, we can begin our study of dc motors.

Direct-current motors transform electrical energy into mechanical energy. They drive devices such as hoists, fans, pumps, calendars, punch-presses, and cars. These devices may have a definite torque-speed characteristic (such as a pump or fan) or a highly variable one (such as a hoist or automobile). The torque-speed characteristic of the motor must be adapted to the type of the load it has to drive, and this requirement has given rise to three basic types of motors:

1. Shunt motors
2. Series motors
3. Compound motors

Direct-current motors are seldom used in ordinary industrial applications because all electric utility systems furnish alternating current. However, for special applications such as in steel mills, mines, and electric trains, it is sometimes advantageous to transform the alternating current into direct current in order to use dc motors. The reason is that the torque-speed characteristics of dc motors can be varied over a wide range while retaining high efficiency.

Today, this general statement can be challenged because the availability of sophisticated electronic drives has made it possible to use alternating current motors for variable speed applications. Nevertheless, there are millions of dc motors still in service and thousands more are being produced every year.

Table of Contents:

- Counter-electromotive force (cemf)
- Acceleration of the motor
- Mechanical power and torque
- Speed of rotation
- Armature speed control

Counter-electromotive force (cemf)

Direct-current motors are built the same way as generators are; consequently, a dc machine can operate either as a motor or as a generator. To illustrate, consider a dc generator in which the armature, initially at rest, is connected to a dc source E_S by means of a switch (Fig. 5.1).

The armature has a resistance R , and the magnetic field is created by a set of permanent magnets.

As soon as the switch is closed, a large current flows in the armature because its resistance is very low. The individual armature conductors are immediately subjected to a force because they are immersed in the magnetic field created by the permanent magnets. These forces add up to produce a powerful torque, causing the armature to rotate.

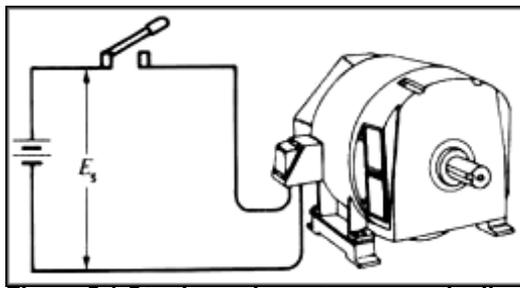


Figure 5.1 Starting a dc motor across the line.

On the other hand, as soon as the armature begins to turn, a second phenomenon takes place: the generator effect. We know that a voltage E_O is induced in the armature conductors as soon as they cut a magnetic field (Fig. 5.2). This is always true, *no matter what causes the rotation*. The value and polarity of the induced voltage are the same as those obtained when the machine operates as a generator. The induced voltage E_O is therefore proportional to the speed of rotation n of the motor and to the flux F per pole, as previously given by Eq. 4.1:

$$E_O = ZnF/60 \quad (4.1)$$

As in the case of a generator, Z is a constant that depends upon the number of turns on the armature and the type of winding. For lap windings Z is equal to the number of armature conductors.

In the case of a motor, the induced voltage E_O is called *counter-electromotive force* (cemf) because its polarity always acts *against* the source voltage E_S . It acts against the voltage in the sense that the net voltage acting in the series circuit of Fig. 5.2 is equal to $(E_S - E_O)$ volts and not $(E_S + E_O)$ volts.

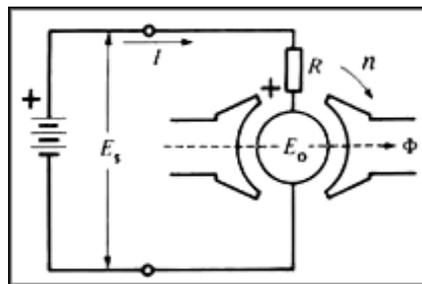


Figure 5.2 Counter-electromotive force (cemf) in a dc motor.

Acceleration of the motor

The net voltage acting in the armature circuit in Fig. 5.2 is $(E_S - E_O)$ volts. The resulting armature current I is limited only by the armature resistance R , and so

$$I = (E_S - E_O)/R \quad (5.1)$$

When the motor is at rest, the induced voltage $E_O = 0$, and so the starting current is

$$I = E_S/R$$

The starting current may be 20 to 30 times greater than the nominal full-load current of the motor. In practice, this would cause the fuses to blow or the circuit-breakers to trip. However, if they are absent, the large forces acting on the armature conductors produce a powerful starting torque and a consequent rapid acceleration of the armature.

As the speed increases, the counter-emf E_O increases, with the result that the value of $(E_S - E_O)$ diminishes. It follows from Eq. 5.1 that the armature current I drops progressively as the speed increases.

Although the armature current decreases, the motor continues to accelerate until it reaches a definite, maximum speed. At no-load this speed produces a counter-emf E_O slightly less than the source voltage E_S . In effect, if E_O were equal to E_S the net voltage $(E_S - E_O)$ would become zero and so, too, would the current I . The driving forces would cease to act on the armature

conductors, and the mechanical drag imposed by the fan and the bearings would immediately cause the motor to slow down. As the speed decreases the net voltage ($E_S - E_O$) increases and so does the current I . The speed will cease to fall as soon as the torque developed by the armature current is equal to the load torque. Thus, when a motor runs at no-load, the counter-emf must be slightly less than E_S so as to enable a small current to flow, sufficient to produce the required torque.

Example 5-1

The armature of a permanent-magnet dc generator has a resistance of 1Ω and generates a voltage of 50 V when the speed is 500 r/min . If the armature is connected to a source of 150 V , calculate the following:

- The starting current
- The counter-emf when the motor runs at 1000 r/min . At 1460 r/min .
- The armature current at 1000 r/min . At 1460 r/min .

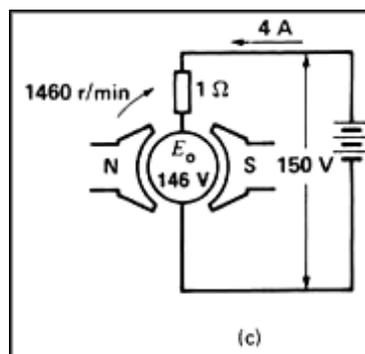
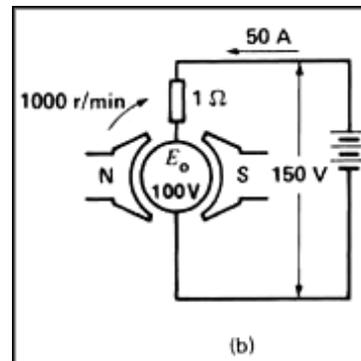
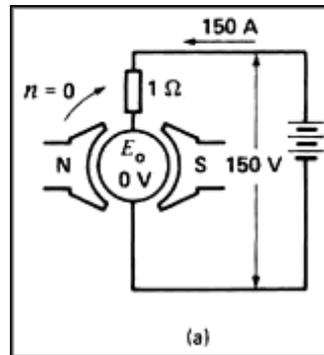


Figure 5.3 See Example 5.1.

Solution

a. At the moment of start-up, the armature is stationary, so $E_O = 0 \text{ V}$ (Fig. 5.3a). The starting current is limited only by the armature resistance:

$$I = E_S / R = 150 \text{ V} / 1 \Omega = 150 \text{ A}$$

b. Because the generator voltage is 50 V at 500 r/min , the cemf of the motor will be 100 V at 1000 r/min and 146 V at 1460 r/min .

c. The net voltage in the armature circuit at 1000 r/min is

$$E_S - E_O = 150 - 100 = 50 \text{ V}$$

The corresponding armature current is

$$\begin{aligned} I &= (E_S - E_O)/R \\ &= 50/1 = 50 \text{ A (Fig.5.3b)} \end{aligned}$$

When the motor speed reaches 1460 r/min, the cemf will be 146 V, almost equal to the source voltage. Under these conditions, the armature current is only

$$\begin{aligned} I &= (E_S - E_O)/R = (150 - 146)/1 \\ &= 4 \text{ A} \end{aligned}$$

and the corresponding motor torque is much smaller than before (Fig. 5.3c).

Mechanical power and torque

The power and torque of a dc motor are two of its most important properties. We now derive two simple equations that enable us to calculate them.

1. According to Eq. 4.1 the cemf induced in a lap-wound armature is given by

$$E_O = ZnF/60 \quad (4.1)$$

Referring to Fig. 5.2, the electrical power P_a supplied to the armature is equal to the supply voltage E_S multiplied by the armature current I :

$$P_a = E_S I \quad (5.2)$$

However, E_S is equal to the sum of E_O plus the IR drop in the armature:

$$E_S = E_O + IR \quad (5.3)$$

It follows that

$$\begin{aligned} P_a &= E_S I \\ &= (E_O + IR)I \\ &= E_O I + I^2 R \quad (5.4) \end{aligned}$$

The $I^2 R$ term represents heat dissipated in the armature, but the very important term $E_O I$ is the electrical power that is converted into mechanical power. The mechanical power of the motor is therefore exactly equal to the product of the cemf multiplied by the armature current

$$P = E_O I \quad (5.5)$$

where

P = mechanical power developed by the motor [W]

E_O = induced voltage in the armature (cemf) [V]

I = total current supplied to the armature [A]

2. Turning our attention to torque T , we know that the mechanical power P is given by the expression

$$P = nT/9.55 \quad (3.5)$$

where n is the speed of rotation.

Combining Eqs. 3.5, 4.1, and 5.5, we obtain

$$\begin{aligned} nT/9.55 &= E_O I \\ &= ZnFI/60 \end{aligned}$$

and so

$$T = ZF I / 6.28$$

The torque developed by a lap-wound motor is therefore given by the expression

$$T = ZF I / 6.28 \quad (5.6)$$

where

T = torque [Nxm]
 Z = number of conductors on the armature
 F = effective flux per pole [Wb]*
 I = armature current [A]
 6.28 = constant, to take care of units
 [exact value = 2π]

Eq. 5.6 shows that we can raise the torque of a motor either by raising the armature current or by raising the flux created by the poles.

Example 5-2

The following details are given on a 225 kW (» 300 hp), 250 V, 1200 r/min dc motor (see Figs. 5.4 and 5.5):

armature coils 243
 turns per coil 1
 type of winding lap
 armature slots 81
 commutator segments 243
 field poles 6
 diameter of armature 559 mm
 axial length of armature 235 mm

* The effective flux is given by $F = 60 E_{\phi} / Z n$.

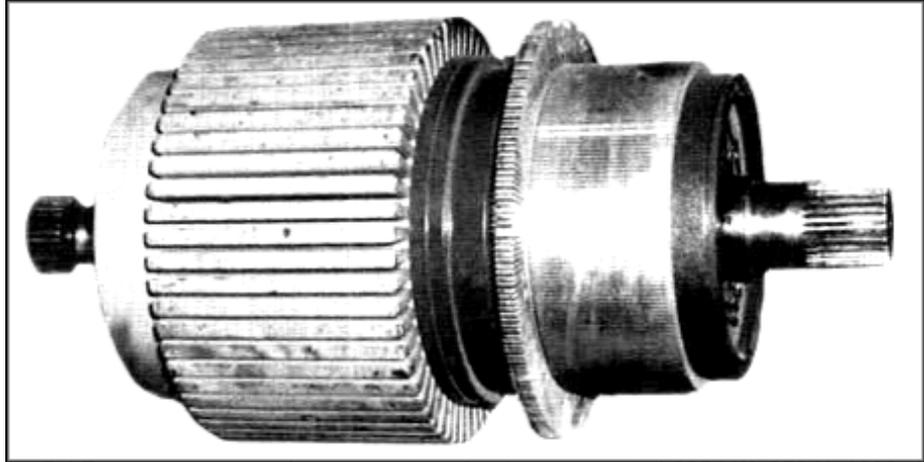
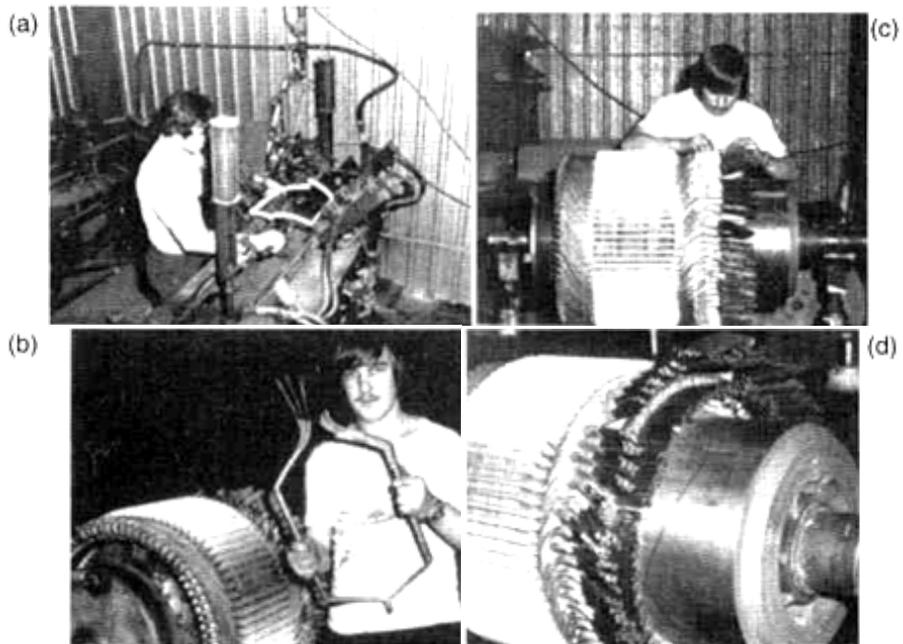


Figure 5.4 Bare armature and commutator of a dc motor rated 225 kW, 250 V, 1200 r/min. The armature core has a diameter of 559 mm and an axial length of 235 mm. It is composed of 400 stacked laminations 0.56 mm thick. The armature has 81 slots and the commutator has 243 bars. (H. Roberge)

**Figure 5.5**

- a. Armature of Fig 5.4 in the process of being wound, coil-forming machine gives the coils the desired shape.
 b One of the 81 coils ready to be placed in the slots
 c Connecting the coil ends to the commutator bars.
 d. Commutator connections ready for brazing (H Roberge)

Calculate

- a. The rated armature current
 b. The number of conductors per slot
 c. The flux per pole

Solution

a. We can assume that the induced voltage E_O is nearly equal to the applied voltage (250 V).
 The rated armature current is

$$I = P/E_O = 225\,000/250 \\ = 900\text{A}$$

b. Each coil is made up of 2 conductors, so altogether there are $243 \times 2 = 486$ conductors on the armature.

$$\text{Conductors per slot} = 486/81 = 6 \\ \text{Coil sides per slot} = 6$$

c. The motor torque is

$$T = 9.55 P/n \\ = 9.55 \times 225\,000/1200 \\ = 1791\text{N}\cdot\text{m}$$

The flux per pole is

$$F = 6.28 T/ZI \\ = (6.28 \times 1790)/(486 \times 900) \\ = 25.7 \text{ mWb}$$

Speed of rotation

When a dc motor drives a load between no-load and full-load, the IR drop due to armature resistance is always small compared to the supply voltage E_S . This means that the counter-emf E_S is very nearly equal to E_S .

On the other hand, we have already seen that E_O may be expressed by the equation

$$E_O = ZnF/60 \quad (4.1)$$

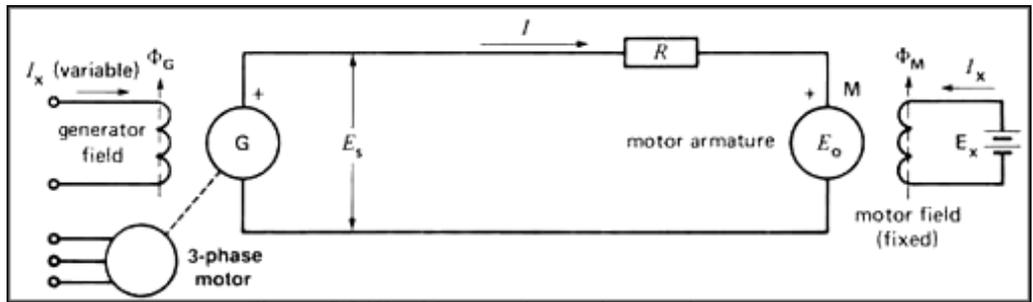


Figure 5.6 Ward-Leonard speed control system.

Replacing E_O by E_S we obtain

$$E_S = ZnF/60$$

That is,

$$n = \frac{60E_S}{Z\Phi} \text{ (approx)}$$

where

n = speed of rotation [r/min]

E_S = armature voltage [V]

Z = total number of armature conductors

This important equation shows that the speed of the motor is directly proportional to the armature supply voltage and inversely proportional to the flux per pole. We will now study how this equation is applied.

Armature speed control

According to Eq. 5.7, if the flux per pole F is kept constant (permanent magnet field or field with fixed excitation), the speed depends only upon the armature voltage E_S . By raising or lowering E_S the motor speed will rise and fall in proportion.

In practice, we can vary E_S by connecting the motor armature M to a separately excited variable-voltage dc generator G (Fig. 5.6). The field excitation of the motor is kept constant, but the generator excitation I_x can be varied from zero to maximum and even reversed. The generator output voltage E_S can therefore be varied from zero to maximum, with either positive or negative polarity. Consequently, the motor speed can be varied from zero to maximum in either direction. Note that the generator is driven by an ac motor connected to a 3-phase line. This method of speed control, known as the Ward-Leonard system, is found in steel mills, high-rise elevators, mines, and paper mills.

In modern installations the generator is often replaced by a high-power electronic converter that changes the ac power of the electrical utility to dc, by electronic means.

The Ward-Leonard system is more than just a simple way of applying a variable dc voltage to the armature of a dc motor. It can actually force the motor to develop the torque and speed required by the load. For example, suppose E_S is adjusted to be slightly higher than the cemf E_O of the motor. Current will then flow in the direction shown in Fig. 5.6, and the motor develops a positive torque. The armature of the motor absorbs power because I flows into the positive terminal.

Now, suppose we reduce E_S by reducing the generator excitation F_G . As soon as E_S becomes less than E_O , current reverses. As a result, (1) the motor torque reverses and (2) the armature of the motor *delivers* power to generator G . In effect, the dc motor suddenly becomes a generator and generator G suddenly becomes a motor. The electric power that the dc motor now delivers to G is derived at the expense of the kinetic energy of the rapidly decelerating armature and its connected mechanical load. Thus, by reducing E_S , the motor is suddenly

forced to slow down.

What happens to the dc power received by generator G? When G receives electric power, it operates as a motor, driving its own ac motor as an asynchronous generator!* As a result, ac power is fed back into the line that normally feeds the ac motor. The fact that power can be recovered this way makes the Ward-Leonard system very efficient, and constitutes another of its advantages.

* The asynchronous generator is explained in Chapter 14.

Example 5-3

A 2000 kW, 500 V, variable-speed motor is driven by a 2500 kW generator, using a Ward-Leonard control system shown in Fig. 5.6. The total resistance of the motor and generator armature circuit is 10 mΩ. The motor turns at a nominal speed of 300 r/min, when E_O is 500 V.

Calculate

a. The motor torque and speed when

$$E_S = 400 \text{ V and } E_O = 380 \text{ V}$$

b. The motor torque and speed when

$$E_S = 350 \text{ V and } E_O = 380 \text{ V}$$

Solution

a. The armature current is

$$\begin{aligned} I &= (E_S - E_O)/R = (400 - 380)/0.01 \\ &= 2000 \text{ A} \end{aligned}$$

The power to the motor armature is

$$P = E_O I = 380 \times 2000 = 760 \text{ kW}$$

The motor speed is

$$n = (380 \text{ V}/500 \text{ V}) \times 300 = 228 \text{ r/min}$$

The motor torque is

$$\begin{aligned} T &= 9.55P/n \\ &= (9.55 \times 760\,000)/228 \\ &= 31.8 \text{ kN}\cdot\text{m} \end{aligned}$$

b. Because $E_O = 380 \text{ V}$, the motor speed is still 228 r/min.

The armature current is

$$\begin{aligned} I &= (E_S - E_O)/R = (350 - 380)/0.01 \\ &= -3000 \text{ A} \end{aligned}$$

The current is negative and so it flows in reverse; consequently, the motor torque also reverses.

Power returned by the motor to the generator and the 10 mΩ resistance:

$$P = E_O I = 380 \times 3000 = 1140 \text{ kW}$$

Braking torque developed by the motor:

$$\begin{aligned} T &= 9.55P/n \\ &= (9.55 \times 1\,140\,000)/228 \\ &= 47.8 \text{ kN}\cdot\text{m} \end{aligned}$$

The speed of the motor and its connected mechanical load will rapidly drop under the influence of this electromechanical braking torque.

Rheostat Speed Control

Another way to control the speed of a dc motor is to place a rheostat in series with the armature

(Fig. 5.7). The current in the rheostat produces a voltage drop which subtracts from the fixed source voltage E_s , yielding a smaller supply voltage across the armature. This method enables us to *reduce* the speed below its nominal speed. It is only recommended for small motors because a lot of power and heat is wasted in the rheostat, and the overall efficiency is low. Furthermore, the speed regulation is poor, even for a fixed setting of the rheostat. In effect, the IR drop across the rheostat increases as the armature current increases. This produces a substantial drop in speed with increasing mechanical load.

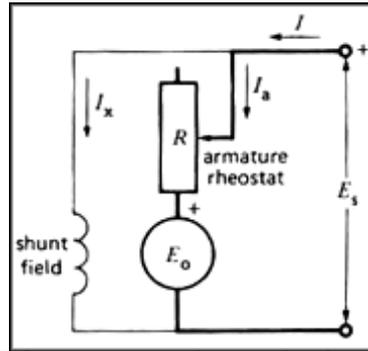


Figure 5.7 Armature speed control using a rheostat.

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DC Motor Calculations, part 2

by Theodore Wildi

Electrical Machines, Drives, and Power Systems, Fourth Edition, Prentice Hall PTR

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Field speed control

According to Eq. 5.7 we can also vary the speed of a dc motor by varying the field flux Φ . Let us now keep the armature voltage E_S constant so that the numerator in Eq. 5.7 is constant. Consequently, the motor speed now changes in inverse proportion to the flux Φ if we increase the flux the speed will drop, and vice versa.

This method of speed control is frequently used when the motor has to run above its rated speed, called *base speed*. To control the flux (and hence, the speed), we connect a rheostat R_f in series with the field (Fig 5 8a).

To understand this method of speed control, suppose that the motor in Fig 5 8a is initially running at constant speed. The counter-emf E_O is slightly less than the armature supply voltage E_S due to the IR drop in the armature. If we suddenly increase the resistance of the rheostat, both the exciting current I_x and the flux Φ will diminish. This immediately reduces the cemf E_O , causing the armature current I to jump to a much higher value. The current changes dramatically because its value depends upon the very small *difference* between E_S and E_O . Despite the weaker field, the motor develops a greater torque than before. It will accelerate until E_O is again almost equal to E_S .

Clearly, to develop the same E_O with a weaker flux, the motor must turn faster. We can therefore raise the motor speed above its nominal value by introducing a resistance in series with the field. For shunt-wound motors, this method of speed control enables high-speed/base-speed ratios as high as 3 to 1. Broader speed ranges tend to produce instability and poor commutation.

Under certain abnormal conditions, the flux may drop to dangerously low values. For example, if the exciting current of a shunt motor is interrupted accidentally, the only flux remaining is that due to the remanent magnetism in the poles. * This flux is so small that the motor has to rotate at a dangerously high speed to induce the required cemf. Safety devices are introduced to prevent such runaway conditions.

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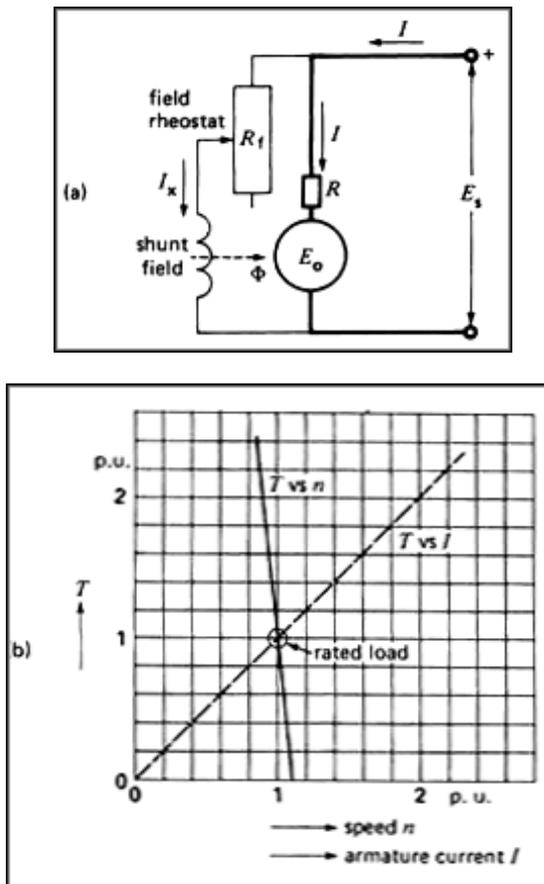


Figure 5.8a. Schematic diagram of a shunt motor including the field rheostat

b. Torque-speed and torque-current characteristic of a shunt motor.

Shunt motor under load

Consider a dc motor running at no-load. If a mechanical load is suddenly applied to the shaft, the small no-load current does not produce enough torque to carry the load and the motor begins to slow down. This causes the cemf to diminish, resulting in a higher current and a corresponding higher torque. When the torque developed by the motor is *exactly* equal to the torque imposed by the mechanical load, then, and only then, will the speed remain constant (see Section 311). To sum up, as the mechanical load increases, the armature current rises and the speed drops.

The speed of a shunt motor stays relatively constant from no-load to full-load. In small motors, it only drops by 10 to 15 percent when full-load is applied. In big machines, the drop is even less, due in part, to the very low armature resistance. By adjusting the field rheostat, the speed can, of course, be kept absolutely constant as the load changes.

* The term *residual magnetism* is also used. However the *IEEE Standard Dictionary of Electrical and Electronics Terms* states 'If there are no air gaps in the magnetic circuit the remanent induction will equal the residual induction if there are air gaps the remanent induction will be less than the residual induction'

Typical torque-speed and torque-current characteristics of a shunt motor are shown in Fig. 5.8b. The speed, torque and current are given in per-unit values. The torque is directly proportional to the armature current. Furthermore, the speed changes only from 1.1 pu to 0.9 pu as the torque increases from 0 pu to 2 pu.

Example 5-4

A shunt motor rotating at 1500 r/min is fed by a 120 V source (Fig. 5.9a). The line current is 51 A and the shunt-field resistance is 120 Ω . If the armature resistance is 0.1 Ω , calculate the following;

a. The current in the armature

- b. The counter-emf
c. The mechanical power developed by the motor

Solution:

- a. The field current (Fig. 5.9b) is

$$I_x = 120\text{V}/120\ \Omega = 1\text{A}$$

The armature current is

$$I = 51 - 1 = 50\text{A}$$

- b. The voltage across the armature is

$$E = 120\text{V}$$

Voltage drop due to armature resistance is

$$IR = 50 \times 0.1 = 5\text{V}$$

The cemf generated by the armature is

$$E_o = 120 - 5 = 115\text{V}$$

- c. The total power supplied to the motor is

$$P_i = EI = 120 \times 51 = 6120\text{W}$$

Power absorbed by the armature is

$$P_a = EI = 120 \times 50 = 6000\text{W}$$

Power dissipated in the armature is

$$P = IR^2 = 50^2 \times 0.1 = 250\text{W}$$

Mechanical power developed by the armature is

$$P = 6000 - 250 = 5750\text{W}$$

(equivalent to $5750/746 = 7.7$ hp)

The actual mechanical output is slightly less than 5750 W because some of the mechanical power is dissipated in bearing friction losses, in windage losses, and in armature iron losses.

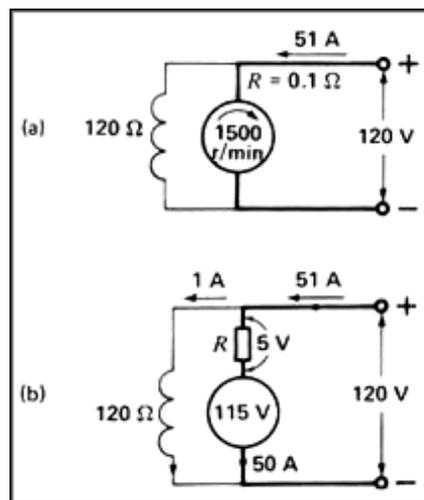


Figure 5.9 See Example 5.4.

Series motor

A series motor is identical in construction to a shunt motor except for the field. The field is connected in series with the armature and must, therefore, carry the full armature current (Fig. 5.10a). This *series field* is composed of a few turns of

wire having a cross section sufficiently large to carry the current. Although the construction is similar, the properties of a series motor are completely different from those of a shunt motor. In a shunt motor, the flux Φ per pole is constant at all loads because the shunt field is connected to the line. But in a series motor the flux per pole depends upon the armature current and, hence, upon the load. When the current is large, the flux is large and vice versa. Despite these differences, the same basic principles and equations apply to both machines.

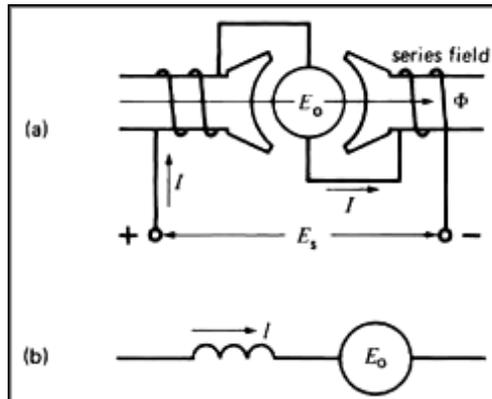


Figure 5.10a. Series motor connection diagram b. Schematic diagram of a series motor

When a series motor operates at full-load, the flux per pole is the same as that of a shunt motor of identical power and speed. However, when the series motor starts up, the armature current is higher than normal, with the result that the flux per pole is also greater than normal. It follows that the starting torque of a series motor is considerably greater than that of a shunt motor. This can be seen by comparing the T versus I curves of Figs 5.8 and 5.11.

On the other hand, if the motor operates at less than full-load, the armature current and the flux per pole are smaller than normal. The weaker field causes the speed to rise in the same way as it would for a shunt motor with a weak shunt field. For example, if the load current of a series motor drops to half its normal value, the flux diminishes by half and so the speed doubles. Obviously, if the load is small, the speed may rise to dangerously high values. For this reason we never permit a series motor to operate at no-load. It tends to run away, and the resulting centrifugal forces could tear the windings out of the armature and destroy the machine.

Series motor speed control

When a series motor carries a load, its speed may have to be adjusted slightly. Thus, the speed can be increased by placing a low resistance in parallel with the series field. The field current is then smaller than before, which produces a drop in flux and an increase in speed.

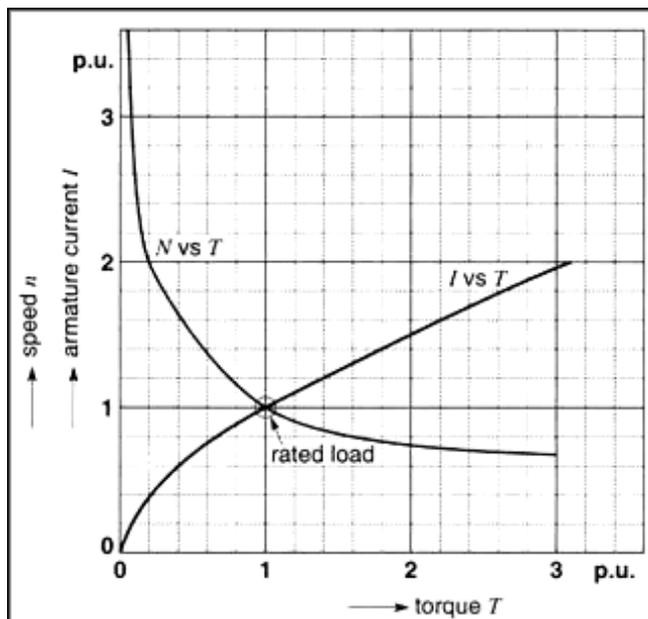


Figure 5.11 Typical speed-torque and current-torque characteristic of a series motor.

Conversely, the speed may be lowered by connecting an external resistor in series with the armature and the field. The total IR drop across the resistor and field reduces the armature supply voltage, and so the speed must fall.

Typical torque-speed and torque-current characteristics are shown in Fig. 5.11. They are quite different from the shunt motor characteristics given in Fig. 5.8b.

Example 5-5

A 15 hp, 240 V, 1780 r/min dc series motor has a full-load rated current of 54 A. Its operating characteristics are given by the per-unit curves of Fig. 5.11.

Calculate

- The current and speed when the load torque is 24 N·m
- The efficiency under these conditions

Solution

a. We first establish the base power, base speed, and base current of the motor. They correspond to the full-load ratings as follows:

$$P_B = 15 \text{ hp} = 15 \times 746 = 11\,190 \text{ W}$$

$$n_B = 1780 \text{ r/min}$$

$$I_B = 54 \text{ A}$$

The base torque is, therefore,

$$\begin{aligned} T_B &= \frac{9.55 P_B}{n_B} = 9.55 \times 11\,190 / 1780 \\ &= 60 \text{ N}\cdot\text{m} \end{aligned}$$

A load torque of 24 N·m corresponds to a per-unit torque of

$$T(\text{pu}) = 24/60 = 0.4$$

Referring to Fig. 5.11, a torque of 0.4 pu is attained at a speed of 1.4 pu. Thus, the speed is

$$n = n(\text{pu}) \times n_B = 1.4 \times 1780$$

$$= 2492 \text{ r/min}$$

From the T vs I curve, a torque of 0.4 pu requires a current of 0.6 pu. Consequently, the load current is

$$I = I(\text{pu}) \times I_B = 0.6 \times 54 = 32.4 \text{ A}$$

b. To calculate the efficiency, we have to know P_O and P_i .

$$P_i = EI = 240 \times 32.4 = 7776 \text{ W}$$

$$P_O = nT/9.55 = 2492 \times 24/9.55$$

$$= 6263 \text{ W}$$

$$h = P_O/P_i = 6263/7776 = 0.805 \text{ or } 80.5\%$$

Applications of the series motor

Series motors are used on equipment requiring a high starting torque. They are also used to drive devices which must run at high speed at light loads. The series motor is particularly well adapted for traction purposes, such as in electric trains. Acceleration is rapid because the torque is high at low speeds. Furthermore, the series motor automatically slows down as the train goes up a grade yet turns at top speed on flat ground. The power of a series motor tends to be constant, because high torque is accompanied by low speed and vice versa. Series motors are also used in electric cranes and hoists: light loads are lifted quickly and heavy loads more slowly. **Related Links:**

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DC Motor Calculations, part 3

by Theodore Wildi

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Compound Motor

A compound dc motor carries both a series field and a shunt field. In a *cumulative compound motor*, the mmf of the two fields add. The shunt field is always stronger than the series field.

Fig. 5.12 shows the connection and schematic diagrams of a compound motor. When the motor runs at no-load, the armature current I_a in the series winding is low and the mmf of the series field is negligible. However, the shunt field is fully excited by current I_x and so the motor behaves like a shunt machine: it does not tend to run away at no-load.

As the load increases, the mmf of the series field increases but the mmf of the shunt field remains constant. The total mmf (and the resulting flux per pole) is therefore greater under load than at no-load. The motor speed falls with increasing load and the speed drop from no-load to full-load is generally between 10 percent and 30 percent.

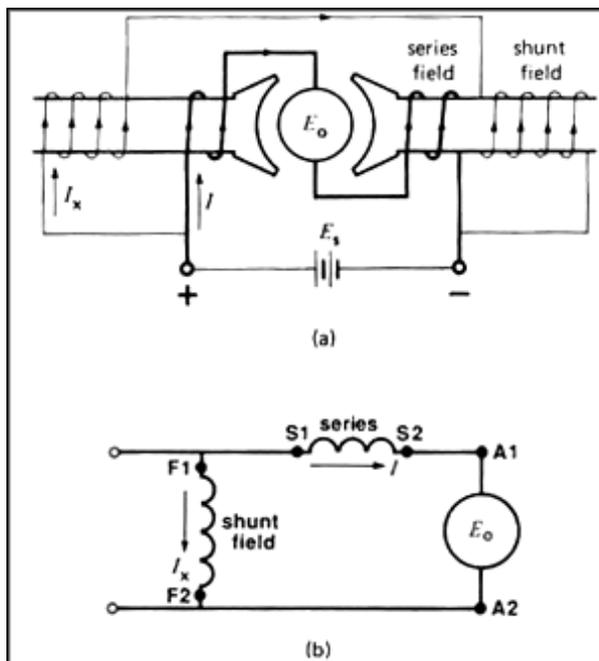


Figure 5.12 a. Connection diagram of a dc compound motor. b. Schematic diagram of the motor.

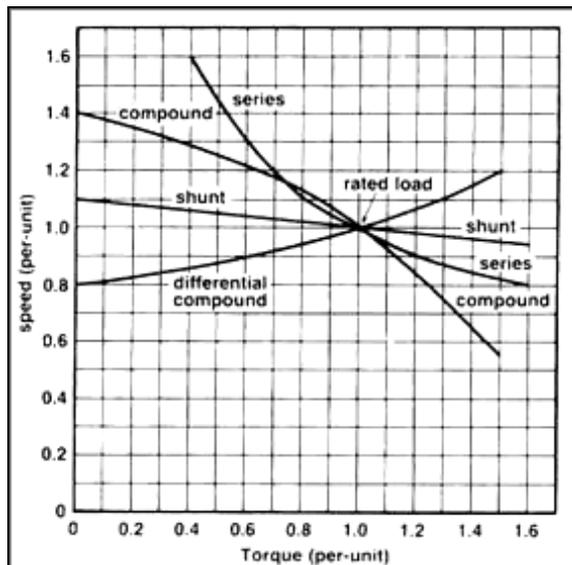


Figure 5.13 Typical speed versus torque characteristics of various dc motors.

If the series field is connected so that it opposes the shunt field, we obtain a *differential compound motor*. In such a motor, the total mmf decreases with increasing load. The speed rises as the load increases, and this may lead to instability. The differential compound motor has very few applications.

Fig. 5.13 shows the typical torque-speed curves of shunt, compound and series motors on a per-unit basis. Fig. 5.14 shows a typical application of dc motors in a steel mill.

Reversing the direction of rotation

To reverse the direction of rotation of a dc motor, we must reverse either (1) the armature connections or (2) both the shunt and series field connections. The interpoles are considered to form part of the armature. The change in connections is shown in Fig. 5.15.

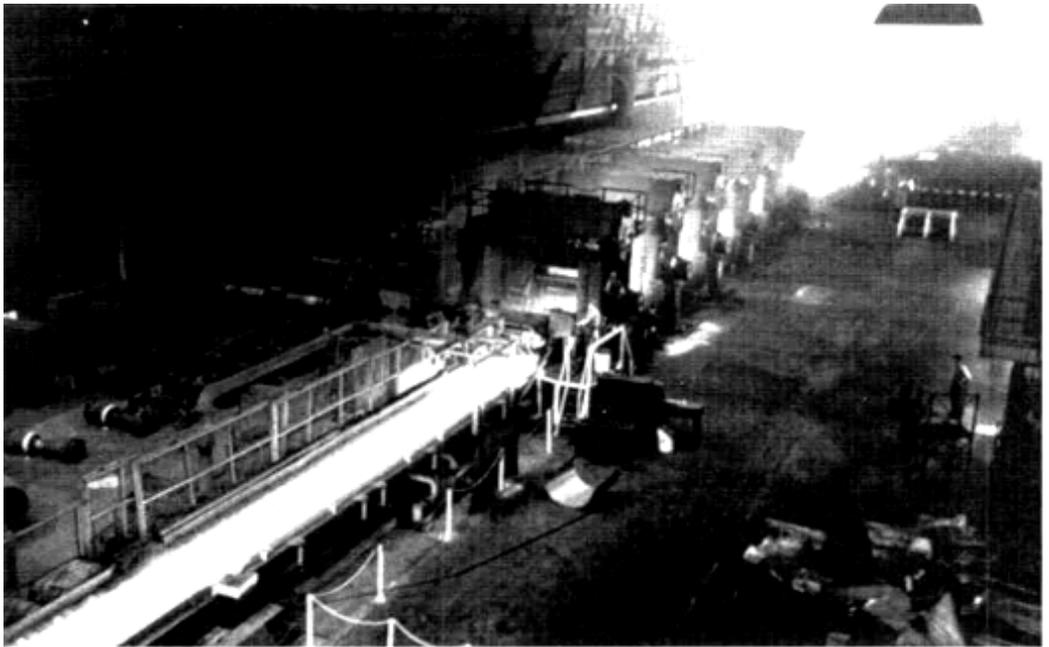


Figure 5.14 Hot strip finishing mill composed of 6 stands, each driven by a 2500 kW dc motor. The wide steel strip is delivered to the runout table (left foreground) driven by 161 dc motors, each rated 3 kW. (Courtesy of General Electric)

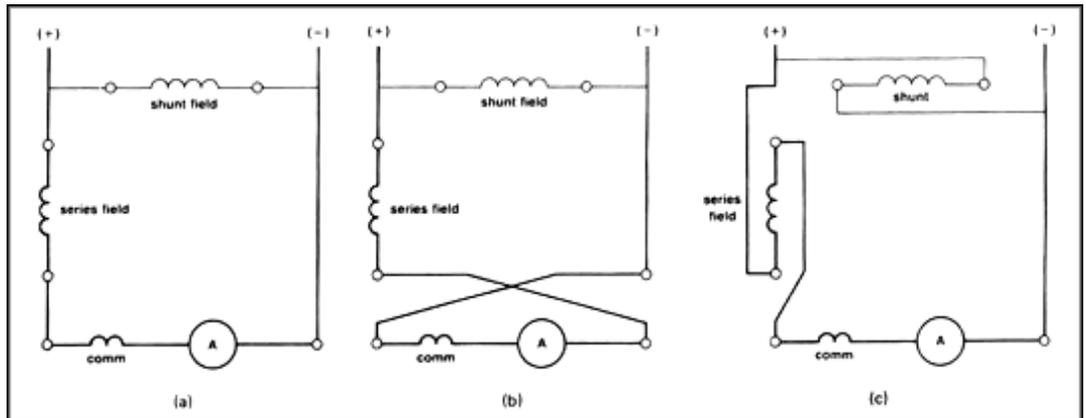


Figure 5.15

- a. Original connections of a compound motor.
- b. Reversing the armature connections to reverse the direction of rotation.
- c. Reversing the field connections to reverse the direction of rotation.

Starting a shunt motor

If we apply full voltage to a stationary shunt motor, the starting current in the armature will be very high and we run the risk of

- a. Burning out the armature;
- b. Damaging the commutator and brushes, due to heavy sparking;
- c. Overloading the feeder;
- d. Snapping off the shaft due to mechanical shock;
- e. Damaging the driven equipment because of the sudden mechanical hammerblow.

All dc motors must, therefore, be provided with a means to limit the starting current to reasonable values, usually between 1.5 and twice full-load current. One solution is to connect a rheostat in series with the armature. The resistance is gradually reduced as the motor accelerates and is eventually eliminated entirely, when the machine has attained full speed.

Today, electronic methods are often used to limit the starting current and to provide speed control.

Face-plate starter

Fig. 5.16 shows the schematic diagram of a manual face-plate starter for a shunt motor. Bare copper contacts are connected to current-limiting resistors R_1 , R_2 , R_3 , and R_4 . Conducting arm 1 sweeps

across the contacts when it is pulled to the right by means of insulated handle 2. In the position shown, the arm touches dead copper contact M and the motor circuit is open. As we draw the handle to the right, the conducting arm first touches fixed contact N.

The supply voltage E_S immediately causes full field current I_x to flow, but the armature current I is limited by the four resistors in the starter box. The motor begins to turn and, as the cemf E_O builds up, the armature current gradually falls. When the motor speed ceases to rise any more, the arm is pulled to the next contact, thereby removing resistor R_1 from the armature circuit. The current immediately jumps to a higher value and the motor quickly accelerates to the next higher speed. When the speed again levels off, we move to the next contact, and so forth, until the arm finally touches the last contact. The arm is magnetically held in this position by a small electromagnet 4, which is in series with the shunt field.

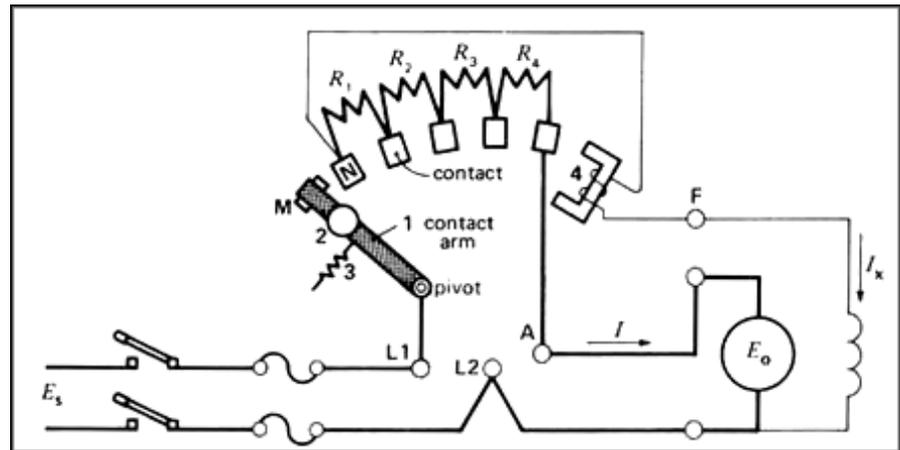


Figure 5.16 Manual face-plate starter for a shunt motor.

If the supply voltage is suddenly interrupted, or if the field excitation should accidentally be cut, the electromagnet releases the arm, allowing it to return to its dead position, under the pull of spring 3. This safety feature prevents the motor from restarting unexpectedly when the supply voltage is reestablished.

Stopping a motor

One is inclined to believe that stopping a dc motor is a simple, almost trivial, operation. Unfortunately, this is not always true. When a large dc motor is coupled to a heavy inertia load, it may take an hour or more for the system to come to a halt. For many reasons such a lengthy deceleration time is often unacceptable and, under these circumstances, we must apply a braking torque to ensure a rapid stop. One way to brake the motor is by simple mechanical friction, in the same way we stop a car. A more elegant method consists of circulating a reverse current in the armature, so as to brake the motor electrically. Two methods are employed to create such an electromechanical brake (1) dynamic braking and (2) plugging.

Dynamic braking

Consider a shunt motor whose field is directly connected to a source E_S , and whose armature is connected to the same source by means of a double-throw switch. The switch connects the armature to either the line or to an external resistor R (Fig. 5.17).

When the motor is running normally, the direction of the armature current I_1 and the polarity of the cemf E_O are as shown in Fig. 5.17a. Neglecting the armature IR drop, E_O is equal to E_S .

If we suddenly open the switch (Fig 5.17b), the motor continues to turn, but its speed will gradually drop due to friction and windage losses. On the other hand, because the shunt field is still excited, induced voltage E_O continues to exist, falling at the same rate as the speed. In essence, the motor is now a generator whose armature is on open-circuit.

Let us close the switch on the second set of contacts so that the armature is suddenly connected to the external resistor (Fig. 5.17c). Voltage E_O will immediately produce an armature current I_2 . However, this current flows in the *opposite* direction to the original current I_1 . It follows that a reverse torque is developed whose magnitude depends upon I_2 . The reverse torque brings the machine to a rapid, but very smooth stop.

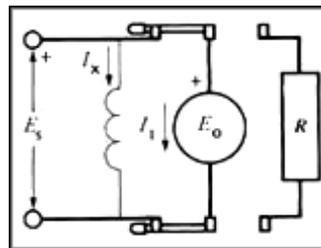


Figure 5.17a Armature connected to a dc source E_s .

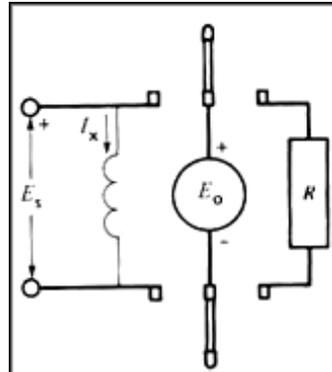


Figure 5.17b Armature on open circuit generating a voltage E_o .

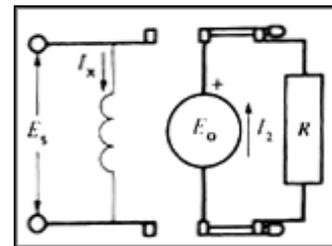


Figure 5.17c Dynamic braking.

In practice, resistor R is chosen so that the initial braking current is about twice the rated motor current. The initial braking torque is then twice the normal torque of the motor.

As the motor slows down, the gradual decrease in E_o produces a corresponding decrease in I_2 . Consequently, the braking torque becomes smaller and smaller, finally becoming zero when the armature ceases to turn. The speed drops quickly at first and then more slowly, as the armature comes to a halt. The speed decreases exponentially, somewhat like the voltage across a discharging capacitor. Consequently, the speed decreases by half in equal intervals of time T_o . To illustrate the usefulness of dynamic braking, Fig. 5.18 compares the speed-time curves for a motor equipped with dynamic braking and one that simply coasts to a stop.

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DC Motor Calculations, part 4

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Plugging

We can stop the motor even more rapidly by using a method called *plugging*. It consists of suddenly reversing the armature current by reversing the terminals of the source (Fig. 5.19a).

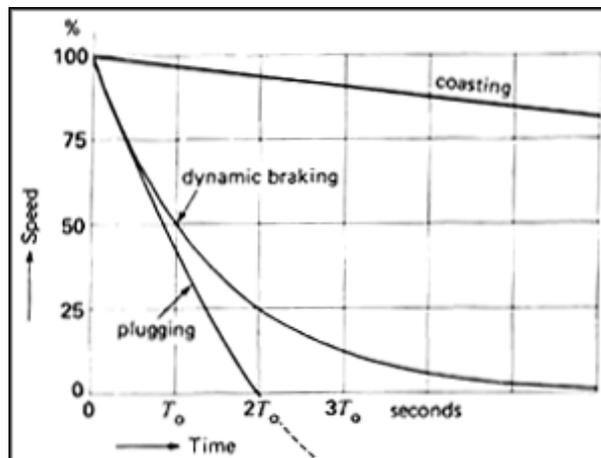


Figure 5.18 Speed versus time curves for various braking methods.

Under normal motor conditions, armature current I_1 is given by

$$I_1 = (E_S - E_O)/R$$

where R is the armature resistance. If we suddenly reverse the terminals of the source, the net voltage acting on the armature circuit becomes $(E_O + E_S)$. The so-called counter-emf E_O of the armature is no longer counter to anything but actually *adds* to the supply voltage E_S . This net voltage would produce an enormous reverse current, perhaps 50 times greater than the full-load

armature current. This current would initiate an arc around the commutator, destroying segments, brushes, and supports, even before the line circuit breakers could open.

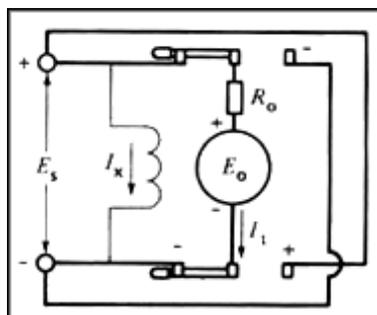


Figure 5.19a Armature connected to dc source E_s .

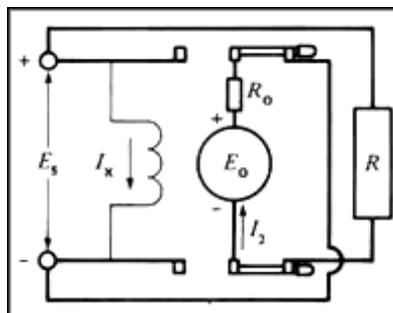


Figure 5.19b Plugging.

To prevent such a catastrophe, we must limit the reverse current by introducing a resistor R in series with the reversing circuit (Fig. 5.19b). As in dynamic braking, the resistor is designed to limit the initial braking current I_2 to about twice full-load current. With this plugging circuit, a reverse torque is developed even when the armature has come to a stop. In effect, at zero speed, $E_o = 0$, but $I_2 = E_s/R$, which is about one-half its initial value. As soon as the motor stops, we must immediately open the armature circuit, otherwise it will begin to run in reverse. Circuit interruption is usually controlled by an automatic null-speed device mounted on the motor shaft.

The curves of Fig. 5.18 enable us to compare plugging and dynamic braking for the same initial braking current. Note that plugging stops the motor completely after an interval $2T_o$. On the other hand, if dynamic braking is used, the speed is still 25 percent of its original value at this time. Nevertheless, the comparative simplicity of dynamic braking renders it more popular in most applications.

Dynamic braking and mechanical time constant

We mentioned that the speed decreases exponentially with time when a dc motor is stopped by dynamic braking. We can therefore speak of a mechanical time constant T in much the same way we speak of the electrical time constant of a capacitor that discharges into a resistor.

In essence, T is the time it takes for the speed of the motor to fall to 36.8 percent of its initial value. However, it is much easier to draw the speed-time curves by defining a new time constant T_o which is the time for the speed to decrease to 50 percent of its original value. There is a direct mathematical relationship between the conventional time constant T and the half-time constant T_o . It is given by

$$T_o = 0.693T \quad (5.8)$$

We can prove that this mechanical time constant is given by

$$T_o = \frac{Jn_1^2}{131.5 P_1} \quad (5.9)$$

where

T_o = time for the motor speed to fall to one-half its previous value [s]

J = moment of inertia of the rotating parts, referred to the motor shaft [kgxm]

n_1 = initial speed of the motor when braking starts [r/min]

P_1 = initial power delivered by the motor to the braking resistor [W]

131.5 = a constant [exact value = $(30/p)^2 \log_e 2$]

0.693 = a constant [exact value = $\log_e 2$]

This equation is based upon the assumption that the braking effect is entirely due to the energy dissipated in the braking resistor. In general, the motor is subjected to an extra braking torque due to windage and friction, and so the braking time will be less than that given by Eq. 5.9.

Example 5-6

A 225 kW (»300 hp), 250 V, 1280 r/min dc motor has windage, friction, and iron losses of 8 kW. It drives a large flywheel and the total moment of inertia of the flywheel and armature is 177 kgxm². The motor is connected to a 210 V dc source, and its speed is 1280 r/min just before the armature is switched across a braking resistor of 0.2 Ω.

Calculate

a. The mechanical time constant T_O of the braking system

b. The time for the motor speed to drop to 20 r/min

c. The time for the speed to drop to 20 r/min if the only braking force is that due to the windage, friction, and iron losses

Solution

a. We note that the armature voltage is 210 V and the speed is 1280 r/min.

When the armature is switched to the braking resistor, the induced voltage is still very close to 210 V. The initial power delivered to the resistor is

$$P_1 = E^2/R = 210^2/0.2 = 220\,500 \text{ W}$$

The time constant T_O is

$$\begin{aligned} T_O &= Jn_1^2/(131.5 P_1) \quad (5.9) \\ &= \frac{177 \times 1280^2}{131.5 \times 220\,500} \\ &= 10\text{s} \end{aligned}$$

b. The motor speed drops by 50 percent every 10 s. The speed versus time curve follows the sequence given below:

speed (r/min)	time(s)
1280	0
640	10
320	20
160	30
80	40
40	50
20	60

The speed of the motor drops to 20 r/min after an interval of 60 s.

c. The initial windage, friction, and iron losses are 8 kW. These losses do not vary with speed in exactly the same way as do the losses in a braking resistor. However, the behavior is comparable, which enables us to make a rough estimate of the braking time. We have

$$n_1 = 1280 \quad P_1 = 8000$$

The new time constant is

$$T_O = Jn_1^2/(131.5 P_1)$$

$$= (177 \times 1280^2) / (131.5 \times 8000)$$

$$= 276 \text{ s} = 4.6 \text{ min}$$

The stopping time increases in proportion to the time constant. Consequently, the time to reach 20 r/min is approximately

$$t = (276/10) \times 60 = 1656 \text{ s} \\ = 28 \text{ min}$$

This braking time is 28 times longer than when dynamic braking is used.

Theoretically, a motor which is dynamically braked never comes to a complete stop. In practice, however, we can assume that the machine stops after an interval equal to $5 T_O$ seconds.

If the motor is plugged, the stopping time has a definite value given by

$$t_S = 2T_O \quad (5.10)$$

where

t_S = stopping time using plugging [s]

T_O = time constant as given in Eq. 5.9 [s]

Example 5-7

The motor in Example 5-6 is plugged, and the braking resistor is increased to 0.4Ω , so that the initial braking current is the same as before.

Calculate

- The initial braking current and braking power
- The stopping time

Solution

The net voltage acting across the resistor is

$$E = E_O + E_S = 210 + 210 = 420 \text{ V}$$

The initial braking current is

$$I_1 = E/R = 420/0.4 = 1050 \text{ A}$$

The initial braking power is

$$P_1 = E_O I_1 = 210 \times 1050 = 220.5 \text{ kW}$$

According to Eq. 5.9, T_O has the same value as before:

$$T_O = 10 \text{ s}$$

The time to come to a complete stop is

$$t_S = 2T_O = 20 \text{ s}$$

Armature reaction

Until now we have assumed that the only mmf acting in a dc motor is that due to the field. However, the current flowing in the armature conductors also creates a magnetomotive force that distorts and weakens the flux coming from the poles. This distortion and field weakening takes place in motors as well as in generators. We recall that the magnetic action of the armature mmf is called *armature reaction*.

Flux distortion due to armature reaction

When a motor runs at no-load, the small current flowing in the armature does not appreciably affect the flux Φ_1 coming from the poles (Fig. 5.20). But when the armature carries its normal

current, it produces a strong magnetomotive force which, if it acted alone, would create a flux Φ_2 (Fig. 5.21). By superimposing Φ_1 and Φ_2 , we obtain the resulting flux Φ_3 (Fig. 5.22). In our example the flux density increases under the left half of the pole and it decreases under the right half. This unequal distribution produces two important effects. First the neutral zone shifts toward the left (against the direction of rotation). The result is poor commutation with sparking at the brushes. Second, due to the higher flux density in pole tip A, saturation sets in. Consequently, the increase of flux under the left-hand side of the pole is less than the decrease under the right-hand side. Flux Φ_3 at full-load is therefore slightly less than flux Φ_1 at no-load. For large machines the decrease in flux may be as much as 10 percent and it causes the speed to increase with load. Such a condition tends to be unstable; to eliminate the problem, we sometimes add a series field of one or two turns to increase the flux under load. Such motors are said to have a *stabilized-shunt winding*.

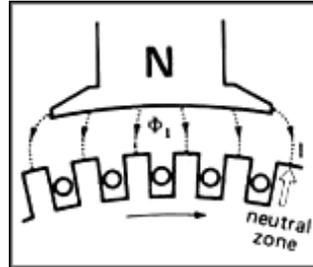


Figure 5.20 Flux distribution in a motor running at no-load.

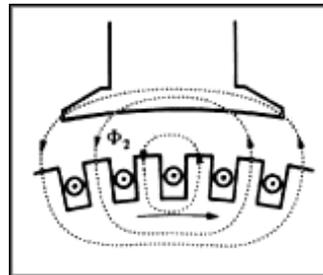


Figure 5.21 Flux created by the full-load armature current.

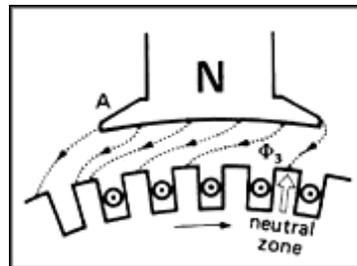


Figure 5.22 Resulting flux distribution in a motor running at full-load.

Commutating poles

To counter the effect of armature reaction and thereby improve commutation, we always place a set of *commutating poles* between the main poles of medium- and large-power dc motors (Fig. 5.23). As in the case of a dc generator, these narrow poles develop a magnetomotive force equal and opposite to the mmf of the armature so that the respective magnetomotive forces rise and fall together as the load current varies. In practice, the mmf of the commutating poles is made slightly greater than that of the armature. Consequently, a small flux subsists in the region of the commutating poles. The flux is designed to induce in the coil undergoing commutation a voltage that is equal and opposite to the self-induction voltage mentioned in Section 4.28. As a result, commutation is greatly improved and takes place roughly as described in Section 4.27.

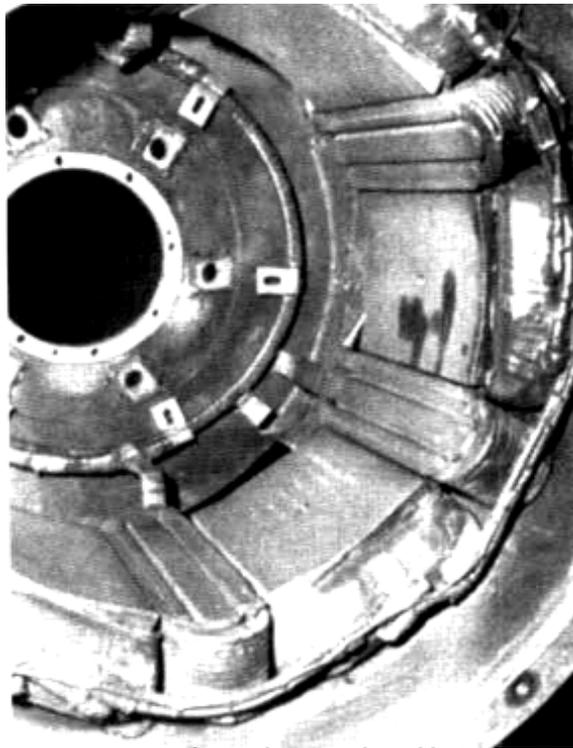


Figure 5.23 The narrow commutating poles are placed between the main poles of this 6-pole motor.

The neutralization of the armature mmf is restricted to the narrow zone covered by the commutating poles, where commutation takes place. The flux distribution under the main poles unfortunately remains distorted. This creates no problem for motors driving ordinary loads. But in special cases it is necessary to add a compensating winding, a feature we will now describe.

Compensating winding

Some dc motors in the 100 kW to 10 MW (≈ 134 hp to 13 400 hp) range employed in steel mills perform a series of rapid, heavy-duty operations. They accelerate, decelerate, stop, and reverse, all in a matter of seconds. The corresponding armature current increases, decreases, reverses in stepwise fashion, producing very sudden changes in armature reaction.

For such motors the commutating poles and series stabilizing windings do not adequately neutralize the armature mmf. Torque and speed control is difficult under such transient conditions and flash-overs may occur across the commutator. To eliminate this problem, special *compensating windings* are connected in series with the armature. They are distributed in slots, cut into the pole faces of the main field poles (Fig. 5.24). Like commutating poles, these windings produce a mmf equal and opposite to the mmf of the armature. However, because the windings are distributed across the pole faces, the armature mmf is bucked from point to point, which eliminates the field distortion shown in Fig 5.22. With compensating windings, the field distribution remains essentially undisturbed from no-load to full-load, retaining the general shape shown in Fig. 5.20.

The addition of compensating windings has a profound effect on the design and performance of a dc motor:

1. A shorter air gap can be used because we no longer have to worry about the demagnetizing effect of the armature. A shorter gap means that the shunt field strength can be reduced and hence the coils are smaller.
2. The inductance of the armature circuit is reduced by a factor of 4 or 5; consequently, the armature current can change more quickly and the motor gives a much better response. This is particularly true in big machines.
3. A motor equipped with compensating windings can briefly develop 3 to 4 times its rated torque. The peak torque of an uncompensated motor is much lower when the armature current is large. The reason is that the effective flux in the air gap falls off rapidly with increasing current because of armature reaction.

We conclude that compensating windings are essential in large motors subjected to severe duty

cycles.

Basics of variable speed control

The most important outputs of a dc motor are its speed and torque. It is useful to determine the limits of each as the speed is increased from zero to above base speed. In so doing, the rated values of armature current, armature voltage, and field flux must not be exceeded, although lesser values may be used.

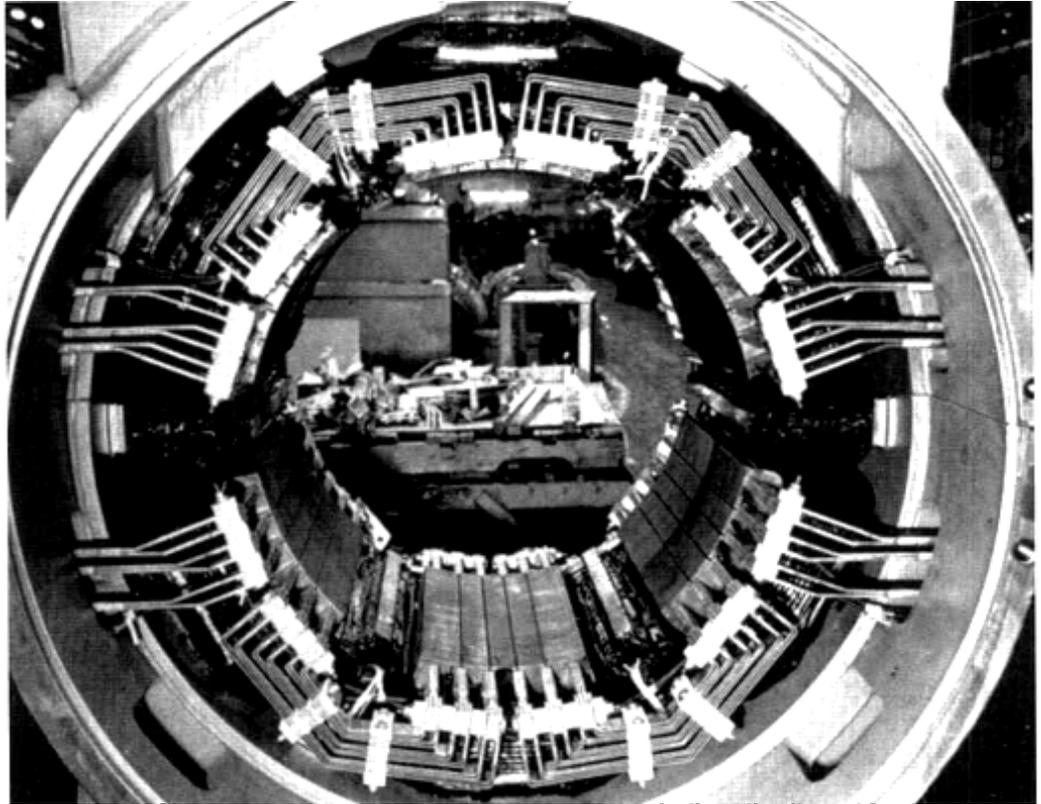


Figure 5.24 Six-pole dc motor having a compensating winding distributed in slots in the main poles. The machine also has 6 commutating poles. (Courtesy of General Electric Company)

In making our analysis, we assume an ideal separately excited shunt motor in which the armature resistance is negligible (Fig. 5.25). The armature voltage E_a , the armature current I_a , the flux Φ_f , the exciting current I_f , and the speed n are all expressed in per-unit values. Thus, if the rated armature voltage E_a happens to be 240 V and the rated armature current I_a is 600 A, they are both given a per-unit value of 1. Similarly, the rated shunt field flux Φ_f has a per-unit value of 1. The advantage of the per-unit approach is that it renders the torque-speed curve universal.

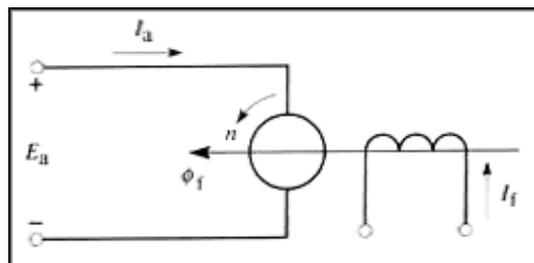


Figure 5.25 Per-unit circuit diagram

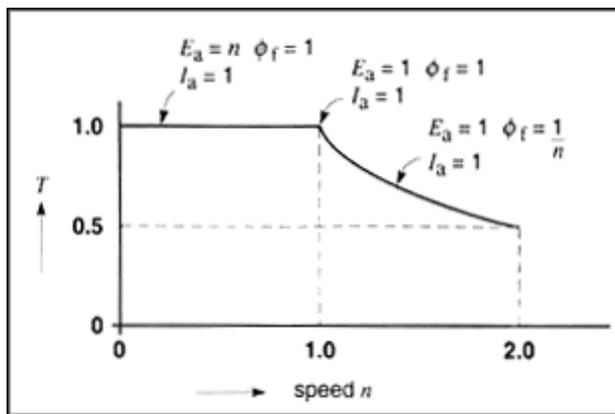


Figure 5.26

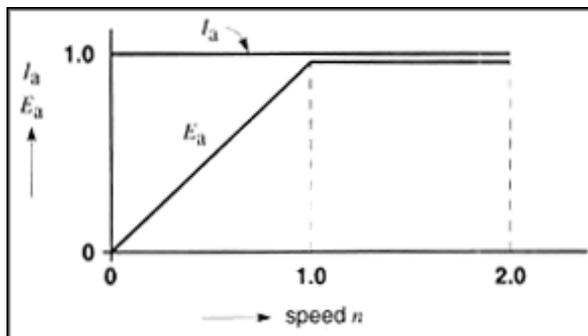


Figure 5.27

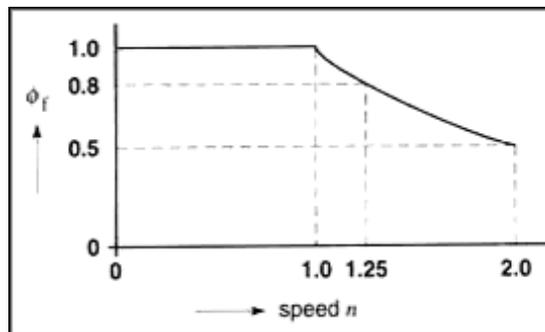


Figure 5.28

Thus, the per-unit torque T is given by the per-unit flux Φ_f times the per-unit armature current I_a

$$T = \Phi_f I_a \quad (5.11)$$

By the same reasoning, the per-unit armature voltage E_a is equal to the per-unit speed n times the per-unit flux Φ_f

$$E_a = n \Phi_f \quad (5.12)$$

The logical starting point of the torque-speed curve (Fig. 5.26), is the condition where the motor develops rated torque ($T = 1$) at rated speed ($n = 1$). The rated speed is often called *base speed*.

In order to reduce the speed below base speed, we gradually reduce the armature voltage to zero, while keeping the rated values of I_a and Φ_f constant at their per-unit value of 1. Applying Eq. (5.11), the corresponding per-unit torque $T = 1 \times 1 = 1$. Furthermore, according to Eq. (5.12), the per-unit voltage $E_a = n \times 1 = n$. Figures 5.27 and 5.28 show the state of E_a , I_a and Φ_f during this phase of motor operation, known as the *constant torque mode*.

Next, to raise the speed above base speed, we realize that the armature voltage cannot be increased anymore because it is already at its rated level of 1. The only solution is to keep E_a at its rated level of 1 and reduce the flux. Referring to Eq. (5.12), this means that $n\Phi_f = 1$, and so $\Phi_f = 1/n$. Thus, above base speed, the per-unit flux is equal to the reciprocal of the per-unit speed. During this operating mode, the armature current can be kept at its rated level of 1. Recalling Eq.

(5.11), it follows that $T = \Phi I_a = (I/n) \times 1 = 1/n$. Consequently, above base speed, the per-unit torque decreases as the reciprocal of the per-unit speed. It is clear that since the per-unit armature current and armature voltage are both equal to 1 during this phase, the power input to the motor is equal to 1. Having assumed an ideal machine, the per-unit mechanical power output is also equal to 1, which corresponds to rated power. That is why the region above base speed is named the *constant horsepower mode*.

We conclude that the ideal dc shunt motor can operate anywhere within the limits of the torque-speed curve depicted in Fig. 5.26.

In practice, the actual torque-speed curve may differ considerably from that shown in Fig. 5.26. The curve indicates an upper speed limit of 2 but some machines can be pushed to limits of 3 and even 4, by reducing the flux accordingly. However, when the speed is raised above base speed, commutation problems develop and centrifugal forces may become dangerous. When the motor runs below base speed, the ventilation becomes poorer and the temperature tends to rise above its rated value. Consequently, the armature current must be reduced, which reduces the torque. Eventually, when the speed is zero, all forced ventilation ceases and even the field current must be reduced to prevent overheating of the shunt field coils. As a result, the permissible stalled torque may only have a per-unit value of 0.25. The resulting practical torque-speed curve is shown in Fig. 5.29.

The drastic fall-off in torque as the speed diminishes can be largely overcome by using an external blower to cool the motor. It delivers a constant stream of air, no matter what the speed of the motor happens to be. Under these conditions, the torque-speed curve approaches that shown in Fig. 5.26.

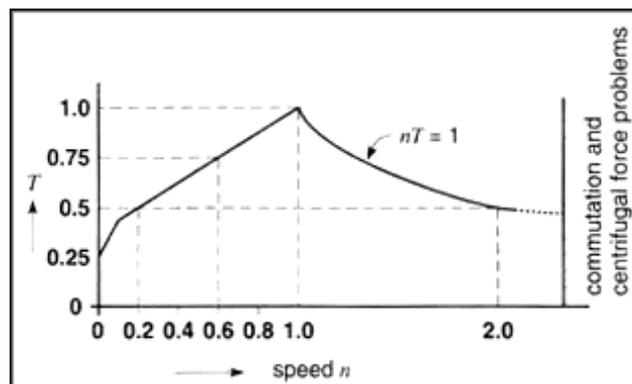


Figure 5.29 Torque-speed curve of a typical dc motor.

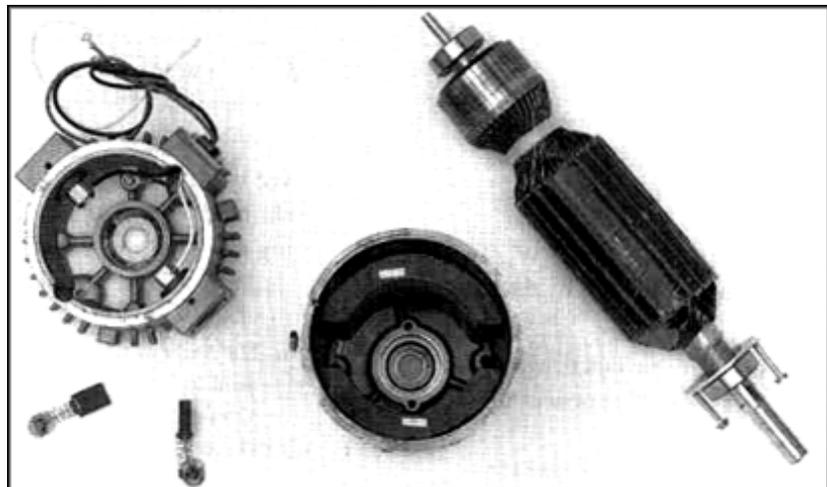


Figure 5.30 Permanent magnet motor rated 1.5 hp, 90 V, 2900 r/min, 14.5 A. Armature diameter: 73 mm; armature length: 115 mm; slots 20; commutator bars: 40; turns per coil; 5; conductor size: No. 17 AWG, lap winding. Armature resistance at 20°C: 0.34 W.
(Courtesy of Baldor Electric Company)

Permanent magnet motors

We have seen that shunt-field motors require coils and a field current to produce the flux. The energy consumed, the heat produced, and the relatively large space taken up by the field poles

are disadvantages of a dc motor. By using permanent magnets instead of field coils, these disadvantages are overcome. The result is a smaller motor having a higher efficiency with the added benefit of never risking run-away due to field failure.

A further advantage of using permanent magnets is that the effective air gap is increased many times. The reason is that the magnets have a permeability that is nearly equal to that of air. As a result, the armature mmf cannot create the intense field that is possible when soft-iron pole pieces are employed. Consequently, the field created by the magnets does not become distorted, as shown in Fig. 5.22. Thus, the armature reaction is reduced and commutation is improved, as well as the overload capacity of the motor. A further advantage is that the long air gap reduces the inductance of the armature and hence it responds much more quickly to changes in armature current.

Permanent magnet motors are particularly advantageous in capacities below about 5 hp. The magnets are ceramic or rare-earth/cobalt alloys. Fig. 5.30 shows the construction of a 1.5 hp, 90 V, 2900 r/min PM motor. Its elongated armature ensures low inertia and fast response when used in servo applications.

The only drawback of PM motors is the relatively high cost of the magnets and the inability to obtain higher speeds by field weakening.

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DC Motor Components

by Thomas E. Kissell

Industrial Electronics, Second Edition, Prentice Hall PTR

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- DC Motor Overview
- Armature
- Motor Frame
- End Plates
- Brushes and Brush Rigging

DC Motor Overview

The armature and field in a DC motor can be wired three different ways to provide varying amounts of torque or different types of speed control. The armature and field windings are designed slightly differently for different types of DC motors. The three basic types of DC motors are the *series motor*, the *shunt motor*, and the *compound motor*. The series motor is designed to move large loads with high starting torque in applications such as a crane motor or lift hoist. The shunt motor is designed slightly differently, since it is made for applications such as pumping fluids, where constant-speed characteristics are important. The compound motor is designed with some of the series motor's characteristics and some of the shunt motor's characteristics. This allows the compound motor to be used in applications where high starting torque and controlled operating speed are both required.

It is important that you understand the function and operation of the basic components of the DC motor, since motor controls will take advantage of these design characteristics to provide speed, torque, and direction of rotation control. Figure 12-5 shows a cutaway picture of a DC motor and Fig. 12-6 shows an exploded-view diagram of a DC motor. In these figures you can see that the basic components include the armature assembly, which includes all rotating parts; the frame assembly, which houses the stationary field coils; and the end plates, which provide bearings for the motor shaft and a mounting point for the brush rigging. Each of these assemblies is explained in depth so that you will understand the design concepts used for motor control.

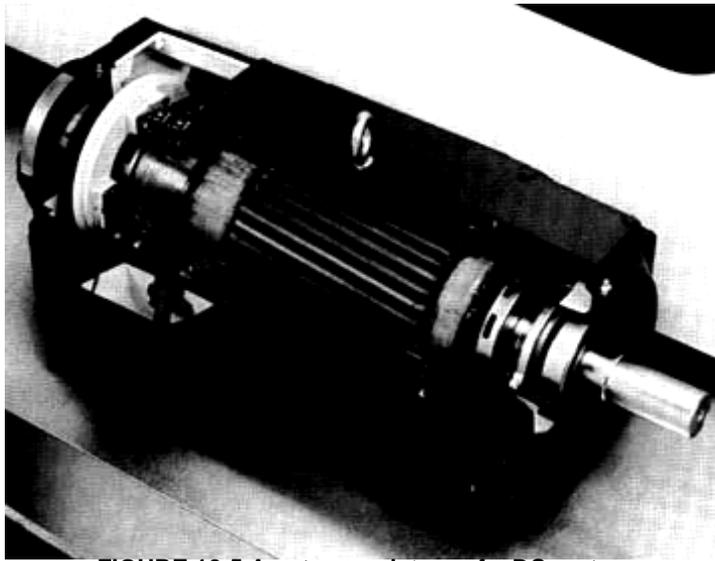


FIGURE 12-5 A cutaway picture of a DC motor.

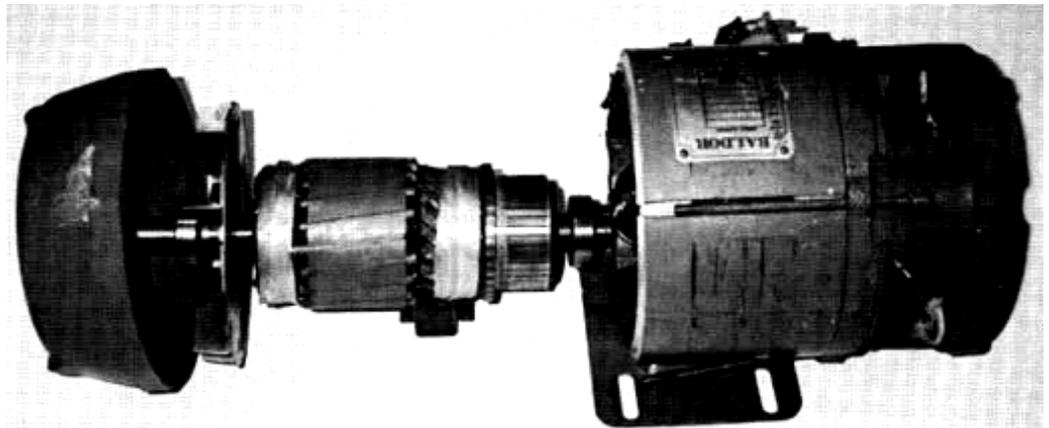


FIGURE 12-6 An exploded view of a DC motor. This diagram shows the relationship of all of the components.

Armature

The armature is the part of a DC motor that rotates and provides energy at the end of the shaft. It is basically an electromagnet, since it is a coil of wire that has to be specially designed to fit around core material on the shaft. The core of the armature is made of laminated steel and provides slots for the coils of wire to be pressed onto. Figure 12-7a shows a sketch of a typical DC motor armature. Figure 12-7b shows the laminated steel core of the armature without any coils of wire on it. This gives you a better look at the core.

The armature core is made of laminated steel to prevent the circulation of eddy currents. If the core were solid, magnetic currents would be produced that would circulate in the core material near the surface and cause the core metal to heat up. These magnetic currents are called *eddy currents*. When laminated steel sections are pressed together to make the core, the eddy currents cannot flow from one laminated segment to another, so they are effectively canceled out. The laminated core also prevents other magnetic losses called *flux losses*. These losses tend to make the magnetic field weaker so that more core material is required to obtain the same magnetic field strengths. The flux losses and eddy current losses are grouped together by designers and called *core losses*. The laminated core is designed to allow the armature's magnetic field to be as strong as possible since the laminations prevent core losses.

Notice that one end of the core has commutator segments. There is one commutator segment for each end of each coil. This means that an armature with four coils will have eight commutator segments. The commutator segments are used as a contact point between the stationary brushes and the rotating armature. When each coil of wire is pressed onto the armature, the end of the coil is soldered to a specific commutator segment. This makes an electrical terminal point for the current that will flow from the brushes onto the commutator segment and finally through the coil of wire. Figure 12-7c shows the coil of wire before it is mounted in the armature slot, and Fig. 12-7d shows the coil mounted in the armature slot and soldered to the commutator segment.

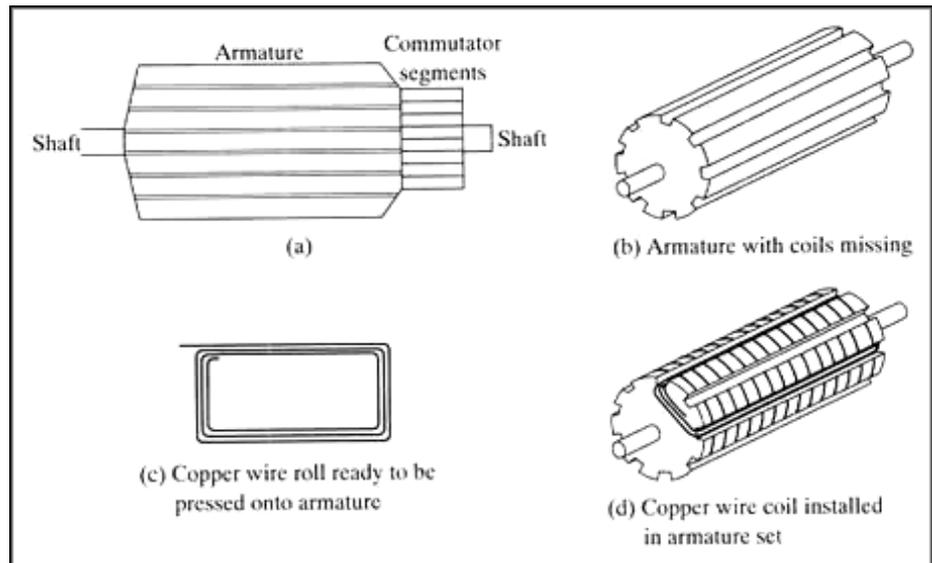


FIGURE 12-7 (a) Armature and commutator segments. (b) Armature prior to the coil's wire being installed. (c) Coil of wire prior to being pressed into the armature. (d) A coil pressed into the armature. The end of each coil is attached to a commutator segment.

The shaft is designed so that the laminated armature segments can be pressed onto it easily. It is also machined to provide a surface for a main bearing to be pressed on at each end. The bearing will ride in the end plates and support the armature when it begins to rotate. One end of the shaft is also longer than the other, since it will provide the mounting shaft for the motor's load to be attached. Some shafts have a key way or flat spot machined into them so that the load that is mounted on it can be secured. You must be careful when handling a motor that you do not damage the shaft, since it must be smooth to accept the coupling mechanism. It is also possible to bend the shaft or cause damage to the bearings so that the motor will vibrate when it is operating at high speed. The commutator is made of copper. A thin section of insulation is placed between each commutator segment. This effectively isolates each commutator segment from all others.

Motor Frame

The armature is placed inside the frame of the motor where the field coils are mounted. When the field coils and the armature coils become magnetized, the armature will begin to rotate. The field winding is made by coiling up a long piece of wire. The wire is mounted on laminated pole pieces called field poles. Similar to an armature, these poles are made of laminated steel or cast iron to prevent eddy current and other flux losses. Figure 12-8 shows the location of the pole pieces inside a DC motor frame.

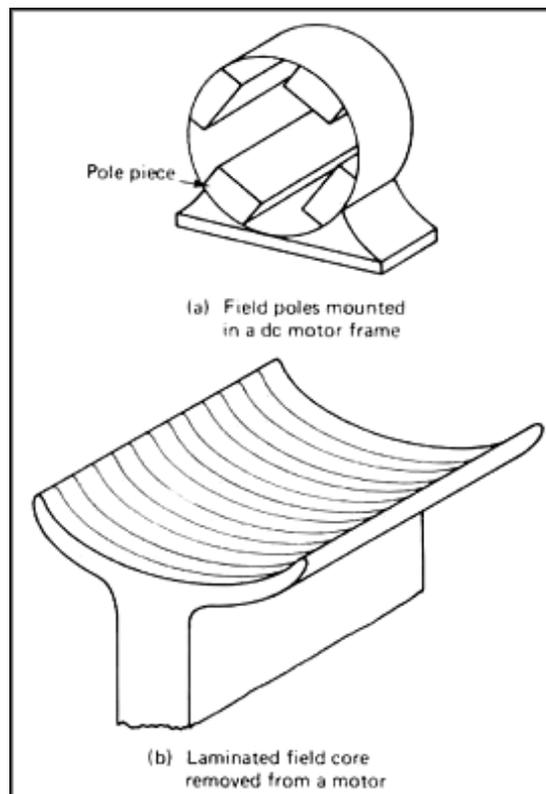


FIGURE 12-8 (a) This diagram shows the location of the pole pieces in the frame of a DC motor. (b) This diagram shows an individual pole piece. You can see that it is made of laminated sections. The field coils are wound around the pole pieces.

The amount of wire that is used to make the field winding will depend on the type of motor that is being manufactured. A series motor uses heavy-gauge wire for its field winding so that it can handle very large field currents. Since the wire is a large gauge, the number of turns of wire in the coil will be limited. If the field winding is designed for a shunt motor, it will be made of small-gauge wire and many turns can be used.

After the coils are wound, they are coated for protection against moisture and other environmental elements. After they have been pressed onto the field poles, they must be secured with shims or bolts so that they are held rigidly in place. Remember: When current is passed through the coil, it will become strongly magnetized and attract or repel the armature magnetic poles. If the field poles are not rigidly secured, they will be pulled loose when they are attracted to the armature's magnetic field and then pressed back into place when they become repelled. This action will cause the field to vibrate and damage the outer protective insulation and cause a short circuit or a ground condition between the winding and the frame of the motor.

The ends of the frame are machined so that the end plates will mount firmly into place. An access hole is also provided in the side of the frame or in the end plates so that the field wires can be brought to the outside of the motor, where DC voltage can be connected.

The bottom of the frame has the mounting bracket attached. The bracket has a set of holes or slots provided so that the motor can be bolted down and securely mounted on the machine it is driving. The mounting holes will be designed to specifications by frame size.

The dimensions for the frame sizes are provided in tables printed by motor manufacturers. Since these holes and slots are designed to a standard, you can predrill the mounting holes in the machinery before the motor is put in place. The slots are used to provide minor adjustments to the mounting alignment when the motor is used in belt-driven or chain-driven applications. It is also important to have a small amount of mounting adjustment when the motor is used in direct-drive applications. It is very important that the motor be mounted so that the armature shaft can turn freely and not bind with the load.

End Plates

The end plates of the motor are mounted on the ends of the motor frame. Figures 12-5 and 12-6 show the location of the end plates in relation to the motor frame. The end plates are held in place by four bolts that pass through the motor frame. The bolts can be removed from the frame completely so that the end plates can be removed easily for maintenance. The end plates also house the bearings for the armature shaft. These bearings can be either sleeve or ball type. If the

bearing is a ball-bearing type, it is normally permanently lubricated. If it is a sleeve type, it will require a light film of oil to operate properly. The end plates that house a sleeve-type bearing will have a lubrication tube and wicking material. Several drops of lubricating oil are poured down the lubrication tube, where they will saturate the wicking material. The wicking is located in the bearing sleeve so that it can make contact with the armature shaft and transfer a light film of oil to it. Other types of sleeve bearings are made of porous metal so that it can absorb oil to be used to create a film between the bearing and the shaft.

It is important that the end plate for a sleeve bearing be mounted on the motor frame so that the lubricating tube is pointing up. This position will ensure that gravity will pull the oil to the wicking material. If the end plates are mounted so that the lubricating tube is pointing down, the oil will flow away from the wicking and it will become dry. When the wicking dries out, the armature shaft will rub directly on the metal in the sleeve bearing, which will cause it to quickly heat up, and the shaft will seize to the bearing. For this reason it is also important to follow lubrication instructions and oil the motor on a regular basis.

Brushes and Brush Rigging

The brush rigging is an assembly that securely holds the brushes in place so that they will be able to ride on the commutator. It is mounted on the rear end plate so that the brushes will be accessible by removing the end plate. An access hole is also provided in the motor frame so that the brushes can be adjusted slightly when the motor is initially set up. The brush rigging uses a spring to provide the proper amount of tension on the brushes so that they make proper contact with the commutator. If the tension is too light, the brushes will bounce and arc, and if the tension is too heavy, the brushes will wear down prematurely.

The brush rigging is shown in Fig. 12-5 and Fig. 12-6. Notice that it is mounted on the rear end plate. Since the rigging is made of metal, it must be insulated electrically when it is mounted on the end plate. The DC voltage that is used to energize the armature will pass through the brushes to the commutator segments and into the armature coils. Each brush has a wire connected to it. The wires will be connected to either the positive or negative terminal of the DC power supply. The motor will always have an even number of brushes. Half of the brushes will be connected to positive voltage and half will be connected to negative voltage. In most motors the number of brush sets will be equal to the number of field poles. It is important to remember that the voltage polarity will remain constant on each brush. This means that for each pair, one of the brushes will be connected to the positive power terminal, and the other will be connected permanently to the negative terminal.

The brushes will cause the polarity of each armature segment to alternate from positive to negative. When the armature is spinning, each commutator segment will come in contact with a positive brush for an instant and will be positive during that time. As the armature rotates slightly, that commutator segment will come in contact with a brush that is connected to the negative voltage supply and it will become negative during that time. As the armature continues to spin, each commutator segment will be alternately powered by positive and then negative voltage.

The brushes are made of carbon-composite material. Usually the brushes have copper added to aid in conduction. Other material is also added to make them wear longer. The end of the brush that rides on the commutator is contoured to fit the commutator exactly so that current will transfer easily. The process of contouring the brush to the commutator is called *seating*. Whenever a set of new brushes is installed, the brushes should be seated to fit the commutator. The brushes are the main part of the DC motor that will wear out. It is important that their wear be monitored closely so that they do not damage the commutator segments when they begin to wear out. Most brushes have a small mark on them called a wear mark or wear bar. When a brush wears down to the mark, it should be replaced. If the brushes begin to wear excessively or do not fit properly on the commutator, they will heat up and damage the brush rigging and spring mechanism. If the brushes have been overheated, they can cause burn marks or pitting on the commutator segments and also warp the spring mechanism so that it will no longer hold the brushes with the proper amount of tension. Figure 12-5 and Fig. 12-6 show the location of the brushes riding on the commutator.

If the spring mechanism has been overheated, it should be replaced and the brushes should be checked for proper operation. If the commutator is pitted, it can be turned down on a lathe. After the commutator has been turned down, the brushes will need to be resealed.

After you have an understanding of the function of each of the parts or assemblies of the motor, you will be able to understand better the operation of a basic DC motor. Operation of the motor involves the interaction of all the motor parts. Some of the parts will be altered slightly for specific motor applications. These changes will become evident when the motor's basic operation is explained.

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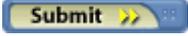
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DC Motor Operation

by Thomas E. Kissell

Industrial Electronics, Second Edition, Prentice Hall PTR

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Electrical Diagram of a DC Motor

The DC motor you will find in modern industrial applications operates very similarly to the simple DC motor described earlier in this chapter. Figure 12-9 shows an electrical diagram of a simple DC motor. Notice that the DC voltage is applied directly to the field winding and the brushes. The armature and the field are both shown as a coil of wire. In later diagrams, a field resistor will be added in series with the field to control the motor speed.

When voltage is applied to the motor, current begins to flow through the field coil from the negative terminal to the positive terminal. This sets up a strong magnetic field in the field winding. Current also begins to flow through the brushes into a commutator segment and then through an armature coil. The current continues to flow through the coil back to the brush that is attached to other end of the coil and returns to the DC power source. The current flowing in the armature coil sets up a strong magnetic field in the armature.

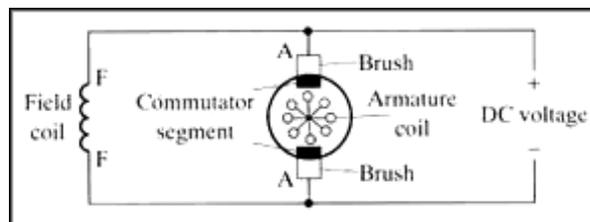


FIGURE 12-9 Simple electrical diagram of DC shunt motor. This diagram shows the electrical relationship between the field coil and armature.

The magnetic field in the armature and field coil causes the armature to begin to rotate. This occurs by the unlike magnetic poles attracting each other and the like magnetic poles repelling each other. As the armature begins to rotate, the commutator segments will also begin to move under the brushes. As an individual commutator segment moves under the brush connected to positive voltage, it will become positive, and when it moves under a brush connected to negative voltage it will become negative. In this way, the commutator segments continually change polarity from positive to negative. Since the commutator segments are connected to the ends of the wires that make up the field winding in the armature, it causes the magnetic field in the armature to change polarity continually from north pole to south pole. The commutator segments and brushes are aligned in such a way that the switch in polarity of the armature coincides with the location of the armature's magnetic field and the field winding's magnetic field. The switching action is timed so that the armature will not lock up magnetically with the field. Instead the magnetic fields tend to build on each other and provide additional torque to keep the motor shaft rotating.

When the voltage is de-energized to the motor, the magnetic fields in the armature and the field winding will quickly diminish and the armature shaft's speed will begin to drop to zero. If voltage is applied to the motor again, the magnetic fields will strengthen and the armature will begin to rotate again.

Types of DC Motors

Three basic types of DC motors are used in industry today: the series motor, the shunt motor, and the compound motor. The series motor is capable of starting with a very large load attached, such as lifting applications. The shunt motor is able to operate with rpm control while it is at high speed. The compound motor, a combination of the series motor and the shunt motor, is able to start with fairly large loads and have some rpm control at higher speeds. In the remaining sections of this chapter we show a diagram for each of these motors and discuss their operational characteristics. As a technician you should understand methods of controlling their speed and ways to change the direction of rotation because these are the two parameters of a DC motor you will be asked to change as applications change on the factory floor. It is also important to understand the basic theory of operation of these motors because you will be controlling them with solid-state electronic circuits. You will need to know if problems that arise are the fault of the motor or the solid-state circuit.

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DC Motor Theory

by Thomas E. Kissell

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DC Motor Overview

The DC motor has two basic parts: the rotating part that is called the *armature*, and the stationary part that includes coils of wire called the *field coils*. The stationary part is also called the *stator*. Figure 12-1 shows a picture of a typical DC motor, Fig. 12-2 shows a picture of a DC armature, and Fig. 12-3 shows a picture of a typical stator. From the picture in Fig. 12-2 you can see the armature is made of coils of wire wrapped around the core, and the core has an extended shaft that rotates on bearings. You should also notice that the ends of each coil of wire on the armature are terminated at one end of the armature. The termination points are called the *commutator*, and this is where the brushes make electrical contact to bring electrical current from the stationary part to the rotating part of the machine.

The picture in Fig. 12-3 shows the location of the coils that are mounted inside the stator. These coils will be referred to as field coils in future discussions and they may be connected in series or parallel with each other to create changes of torque in the motor. You will find the size of wire in these coils and the number of turns of wire in the coil will depend on the effect that is trying to be achieved.



FIGURE 12-1 A typical DC motor.

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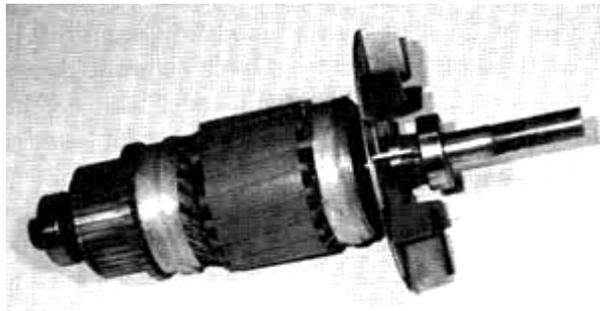


FIGURE 12-2 The armature (rotor) of a DC motor has coils of wire wrapped around its core. The ends of each coil are terminated at commutator segments located on the left end of the shaft. The brushes make contact on the commutator to provide current for the armature.



FIGURE 12-3 The stationary part of a DC motor has the field coils mounted in it.

Magnetic Diagram of a DC Motor

It will be easier to understand the operation of the DC motor from a basic diagram that shows the magnetic interaction between the rotating armature and the stationary field's coils. Figure 12-4 shows three diagrams that explain the DC motor's operation in terms of the magnetic interaction. In Fig. 12-4a you can see that a bar magnet has been mounted on a shaft so that it can spin. The field winding is one long coil of wire that has been separated into two sections. The top section is connected to the positive pole of the battery and the bottom section is connected to the negative pole of the battery. It is important to understand that the battery represents a source of voltage for this winding. In the actual industrial-type motor this voltage will come from the DC voltage source for the motor. The current flow in this direction makes the top coil the north pole of the magnet and the bottom coil the south pole of the magnet. The bar magnet represents the *armature* and the coil of wire represents *the field*. The arrow shows the direction of the armature's rotation. Notice that the arrow shows the armature starting to rotate in the clockwise direction. The north pole of the field coil is repelling the north pole of the armature, and the south pole of the field coil is repelling the south pole of the armature.

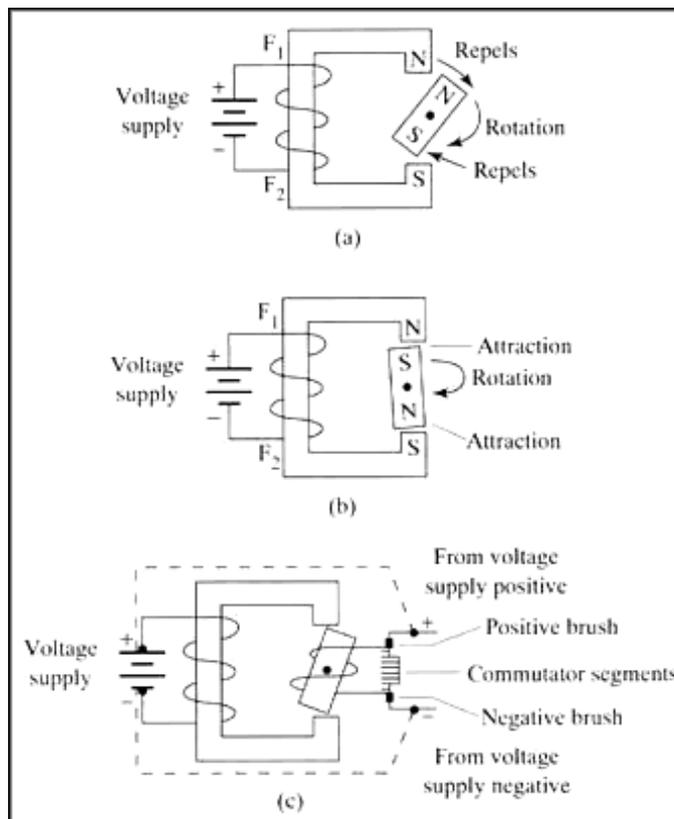


FIGURE 12-4 (a) Magnetic diagram that explains the operation of a DC motor. The rotating magnet moves clockwise because like poles repel. (b) The rotating magnet is being attracted because the poles are unlike. (c) The rotating magnet is now shown as the armature coil, and its polarity is determined by the brushes and commutator segments.

As the armature begins to move, the north pole of the armature comes closer to the south pole of the field, and the south pole of the armature is coming closer to the north pole of the field. As the two unlike poles near each other, they begin to attract. This attraction becomes stronger until the armature's north pole moves directly in line with the field's south pole, and its south pole moves directly in line with the field's north pole (Fig. 12-4b).

When the opposite poles are at their strongest attraction, the armature will be "locked up" and will resist further attempts to continue spinning. For the armature to continue its rotation, the armature's polarity must be switched. Since the armature in this diagram is a permanent magnet, you can see that it would lock up during the first rotation and not work. If the armature is an electromagnet, its polarity can be changed by changing the direction of current flow through it. For this reason the armature must be changed to a coil (electromagnet) and a set of commutator segments must be added to provide a means of making contact between the rotating member and the stationary member. One commutator segment is provided for each terminal of the magnetic coil. Since this armature has only one coil, it will have only two terminals, so the commutator has two segments.

Since the armature is now a coil of wire, it will need DC current flowing through it to become magnetized. This presents another problem; since the armature will be rotating, the DC voltage wires cannot be connected directly to the armature coil. A stationary set of carbon brushes is used to make contact to the rotating armature. The brushes ride on the commutator segments to make contact so that current will flow through the armature coil.

In Fig. 12-4c you can see that the DC voltage is applied to the field and to the brushes. Since negative DC voltage is connected to one of the brushes, the commutator segment the negative brush rides on will also be negative. The armature's magnetic field causes the armature to begin to rotate. This time when the armature gets to the point where it becomes locked up with the magnetic field, the negative brush begins to touch the end of the armature coil that was previously positive and the positive brush begins to touch the end of the armature coil that was negative. This action switches the direction of current flow through the armature, which also switches the polarity of the armature coil's

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DC Series Motors

by Thomas E. Kissell

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- Reversing the Rotation
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Series Motor Diagram

The series motor provides high starting torque and is able to move very large shaft loads when it is first energized. Figure 12-10 shows the wiring diagram of a series motor. From the diagram you can see that the field winding in this motor is wired in series with the armature winding. This is the attribute that gives the series motor its name.

Since the series field winding is connected in series with the armature, it will carry the same amount of current that passes through the armature. For this reason the field is made from heavy-gauge wire that is large enough to carry the load. Since the wire gauge is so large, the winding will have only a few turns of wire. In some larger DC motors, the field winding is made from copper bar stock rather than the conventional round wire used for power distribution. The square or rectangular shape of the copper bar stock makes it fit more easily around the field pole pieces. It can also radiate more easily the heat that has built up in the winding due to the large amount of current being carried.

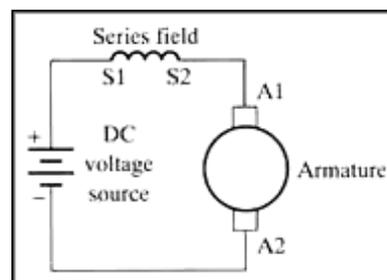


FIGURE 12-10 Electrical diagram of series motor. Notice that the series field is identified as S1 and S2.

The amount of current that passes through the winding determines the amount of torque the motor shaft can produce. Since the series field is made of large conductors, it can carry large amounts of current and produce large torques. For example, the starter motor that is used to start an automobile's engine is a series motor and it may draw up to 500 A when it is turning the engine's crankshaft on a cold morning. Series motors used to power hoists or cranes may

draw currents of thousands of amperes during operation.

The series motor can safely handle large currents since the motor does not operate for an extended period. In most applications the motor will operate for only a few seconds while this large current is present. Think about how long the starter motor on the automobile must operate to get the engine to start. This period is similar to that of industrial series motors.

Series Motor Operation

Operation of the series motor is easy to understand. In Fig. 12-10 you can see that the field winding is connected in series with the armature winding. This means that power will be applied to one end of the series field winding and to one end of the armature winding (connected at the brush).

When voltage is applied, current begins to flow from negative power supply terminals through the series winding and armature winding. The armature is not rotating when voltage is first applied, and the only resistance in this circuit will be provided by the large conductors used in the armature and field windings. Since these conductors are so large, they will have a small amount of resistance. This causes the motor to draw a large amount of current from the power supply. When the large current begins to flow through the field and armature windings, it causes a strong magnetic field to be built. Since the current is so large, it will cause the coils to reach saturation, which will produce the strongest magnetic field possible.

Producing Back EMF

The strength of these magnetic fields provides the armature shafts with the greatest amount of torque possible. The large torque causes the armature to begin to spin with the maximum amount of power. When the armature begins to rotate, it begins to produce voltage. This concept is difficult for some students to understand since the armature is part of the motor at this time.

You should remember from the basic theories of magnetism that anytime a magnetic field passes a coil of wire, a current will be produced. The stronger the magnetic field is or the faster the coil passes the flux lines, the more current will be generated. When the armature begins to rotate, it will produce a voltage that is of opposite polarity to that of the power supply. This voltage is called *back voltage*, *back EMF* (electromotive force), or *counter EMF*. The overall effect of this voltage is that it will be subtracted from the supply voltage so that the motor windings will see a smaller voltage potential.

When Ohm's law is applied to this circuit, you will see that when the voltage is slightly reduced, the current will also be reduced slightly. This means that the series motor will see less current as its speed is increased. The reduced current will mean that the motor will continue to lose torque as the motor speed increases. Since the load is moving when the armature begins to pick up speed, the application will require less torque to keep the load moving. This works to the motor's advantage by automatically reducing the motor current as soon as the load begins to move. It also allows the motor to operate with less heat buildup.

This condition can cause problems if the series motor ever loses its load. The load could be lost when a shaft breaks or if a drive pin is sheared. When this occurs, the load current is allowed to fall to a minimum, which reduces the amount of back EMF that the armature is producing. Since the armature is not producing a sufficient amount of back EMF and the load is no longer causing a drag on the shaft, the armature will begin to rotate faster and faster. It will continue to increase rotational speed until it is operating at a very high speed. When the armature is operating at high speed, the heavy armature windings will be pulled out of their slots by centrifugal force. When the windings are pulled loose, they will catch on a field winding pole piece and the motor will be severely damaged. This condition is called *runaway* and you can see why a DC series motor must have some type of runaway protection. A centrifugal switch can be connected to the motor to de-energize the motor starter coil if the rpm exceeds the set amount. Other sensors can be used to de-energize the circuit if the motor's current drops while full voltage is applied to the motor. The most important part to remember about a series motor is that it is difficult to control its speed by external means because its rpm is determined by the size of its load. (In some smaller series motors, the speed can be controlled by placing a rheostat in series with the supply voltage to provide some amount of change in resistance to control the voltage to the motor.)

Figure 12-11 shows the relationship between series motor speed and armature current. From this curve you can see that when current is low (at the top left), the motor speed is maximum, and when current increases, the motor speed slows down (bottom right). You can also see from this curve that a DC motor will run away if the load current is reduced to zero. (It should be noted that in larger series machines used in industry, the amount of friction losses will limit the highest speed somewhat.)

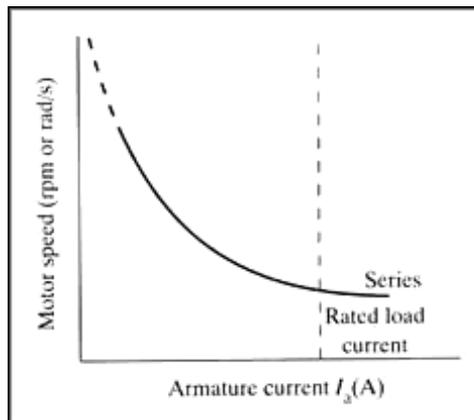


FIGURE 12-11 The relationship between series motor speed and the armature current.

Reversing the Rotation

The direction of rotation of a series motor can be changed by changing the polarity of either the armature or field winding. It is important to remember that if you simply changed the polarity of the applied voltage, you would be changing the polarity of both field and armature windings and the motor's rotation would remain the same.

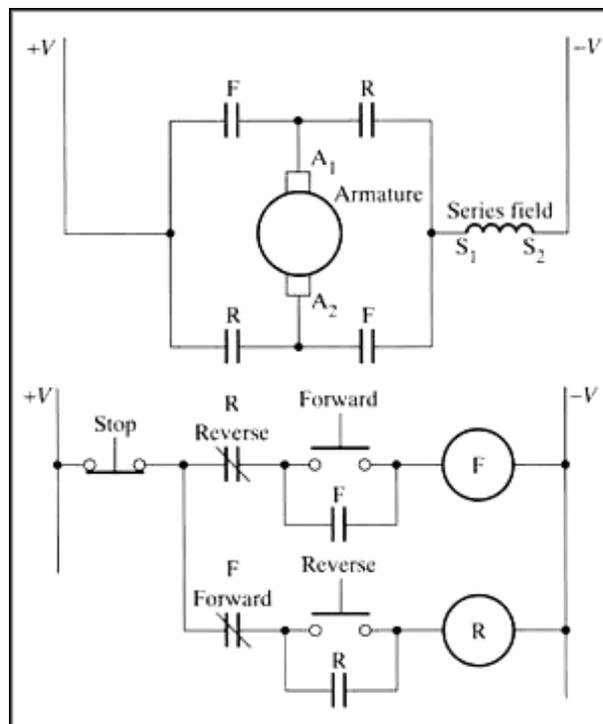


FIGURE 12-12 DC series motor connected to forward and reverse motor starter.

Since only one of the windings needs to be reversed, the armature winding is typically used because its terminals are readily accessible at the brush rigging. Remember that the armature receives its current through the brushes, so that if their polarity is changed, the armature's polarity will also be changed. A reversing motor starter is used to change wiring to cause the direction of the

motor's rotation to change by changing the polarity of the armature windings. Figure 12-12 shows a DC series motor that is connected to a re-versing motor starter. In this diagram the armature's terminals are marked A1 and A2 and the field terminals are marked S1 and S2.

When the forward motor starter is energized, the top contact identified as F closes so the A1 terminal is connected to the positive terminal of the power supply and the bottom F contact closes and connects terminals A2 and S1. Terminal S2 is connected to the negative terminal of the power supply. When the reverse motor starter is energized, terminals A1 and A2 are reversed. A2 is now connected to the positive terminal. Notice that S2 remains connected to the negative terminal of the power supply terminal. This ensures that only the armature's polarity has been changed and the motor will begin to rotate in the opposite direction.

You will also notice the normally closed (NC) set of R contacts connected in series with the forward push button, and the NC set of F contacts connected in series with the reverse push button. These contacts provide an *interlock* that prevents the motor from being changed from forward to reverse direction without stopping the motor. The circuit can be explained as follows: when the forward push button is depressed, current will flow from the stop push button through the NC R interlock contacts, and through the forward push button to the forward motor starter (FMS) coil. When the FMS coil is energized, it will open its NC contacts that are connected in series with the reverse push button. This means that if someone depresses the reverse push button, current could not flow to the reverse motor starter (RMS) coil. If the person depressing the push buttons wants to reverse the direction of the rotation of the motor, he or she will need to depress the stop push button first to de-energize the FMS coil, which will allow the NC F contacts to return to their NC position. You can see that when the RMS coil is energized, its NC R contacts that are connected in series with the forward push button will open and prevent the current flow to the FMS coil if the forward push button is depressed. You will see a number of other ways to control the FMS and RMS starter in later discussions and in the chapter on motor controls.

Installing and Troubleshooting

Since a series motor has only two leads brought out of the motor for installation wiring, this wiring can be accomplished rather easily. If the motor is wired to operate in only one direction, the motor terminals can be connected to a manual or magnetic starter. If the motor's rotation is required to be reversed periodically, it should be connected to a reversing starter.

Most DC series motors are used in direct-drive applications. This means that the load is connected directly to the armature's shaft. This type of load is generally used to get the most torque converted. Belt-drive applications are not recommended since a broken belt would allow the motor to run away. After the motor has been installed, a test run should be used to check it out. If any problems occur, the troubleshooting procedures should be used.

The most likely problem that will occur with the series motor is that it will develop an open in one of its windings or between the brushes and the commutator. Since the coils in a series motor are connected in series, each coil must be functioning properly or the motor will not draw any current. When this occurs, the motor cannot build a magnetic field and the armature will not turn. Another problem that is likely to occur with the motor circuit is that circuit voltage will be lost due to a blown fuse or circuit breaker. The motor will respond similarly in both of these conditions.

The best way to test a series motor is with a voltmeter. The first test should be for applied voltage at the motor terminals. Since the motor terminals are usually connected to a motor starter, the test leads can be placed on these terminals. If the meter shows that full voltage is applied, the problem will be in the motor. If it shows that no voltage is present, you should test the supply voltage and the control circuit to ensure that the motor starter is closed. If the motor starter has a visual indicator, be sure to check to see that the starter's contacts are closed. If the overloads have tripped, you can assume that they have sensed a problem with the motor or its load. When you reset the overloads, the motor will probably start again but remember to test the motor thoroughly for problems that would cause an overcurrent situation.

If the voltage test indicates that the motor has full applied voltage to its terminals but the motor is not operating, you can assume that you have an open in one of

the windings or between the brushes and the armature and continue testing. Each of these sections should be disconnected from each other and voltage should be removed so that they can be tested with an ohmmeter for an open. The series field coils can be tested by putting the ohmmeter leads on terminals S1 and S2. If the meter indicates that an open exists, the motor will need to be removed and sent to be rewound or replaced. If the meter indicates that the field coil has continuity, you should continue the procedure by testing the armature.

The armature can also be tested with an ohmmeter by placing the leads on the terminals marked A1 and A2. If the meter shows continuity, rotate the armature shaft slightly to look for bad spots where the commutator may have an open or the brushes may not be seated properly. If the armature test indicates that an open exists, you should continue the test by visually inspecting the brushes and commutator. You may also have an open in the armature coils. The armature must be removed from the motor frame to be tested further. When you have located the problem, you should remember that the commutator can be removed from the motor while the motor remains in place and it can be turned down on a lathe. When the commutator is replaced in the motor, new brushes can be installed and the motor will be ready for use.

It is possible that the motor will develop a problem but still run. This type of problem usually involves the motor overheating or not being able to pull its rated load. This type of problem is different from an open circuit because the motor is drawing current and trying to run. Since the motor is drawing current, you must assume that there is not an open circuit. It is still possible to have brush problems that would require the brushes to be re-seated or replaced. Other conditions that will cause the motor to overheat include loose or damaged field and armature coils. The motor will also overheat if the armature shaft bearing is in need of lubrication or is damaged. The bearing will seize on the shaft and cause the motor to build up friction and overheat.

If either of these conditions occurs, the motor may be fixed on site or be removed for extensive repairs. When the motor is restarted after repairs have been made, it is important to monitor the current usage and heat buildup. Remember that the motor will draw DC current so that an AC clamp-on ammeter will not be useful for measuring the DC current. You will need to use an ammeter that is specially designed for very large DC currents. It is also important to remember that the motor can draw very high locked-rotor current when it is starting, so the ammeter should be capable of measuring currents up to 1000 A. After the motor has completed its test run successfully, it can be put back into operation for normal duty. Anytime the motor is suspected of faulty operation, the troubleshooting procedure should be rechecked.

DC Series Motor Used as a Universal Motor

The series motor is used in a wide variety of power tools such as electric hand drills, saws, and power screwdrivers. In most of these cases, the power source for the motor is AC voltage. The DC series motor will operate on AC voltage. If the motor is used in a hand drill that needs variable-speed control, a field rheostat or other type of current control is used to control the speed of the motor. In some newer tools, the current control uses solid-state components to control the speed of the motor. You will notice that the motors used for these types of power tools have brushes and a commutator, and these are the main parts of the motor to wear out. You can use the same theory of operation provided for the DC motor to troubleshoot these types of motors.

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DC Shunt Motors

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Electrical Diagram of a Shunt Motor

The shunt motor is different from the series motor in that the field winding is connected in parallel with the armature instead of in series. You should remember from basic electrical theory that a parallel circuit is often referred to as a shunt. Since the field winding is placed in parallel with the armature, it is called a shunt winding and the motor is called a shunt motor. Figure 12-13 shows a diagram of a shunt motor. Notice that the field terminals are marked F1 and F2, and the armature terminals are marked A1 and A2. You should notice in this diagram that the shunt field is represented with multiple turns using a thin line.

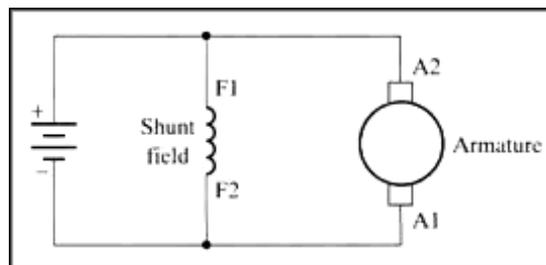


FIGURE 12-13 Diagram of DC shunt motor. Notice the shunt coil is identified as a coil of fine wire with many turns that is connected in parallel (shunt) with the armature.



FIGURE 12-14 Typical DC shunt motor. These motors are available in a variety of sizes. This motor is a 1 hp (approximately 8 in. tall).

The shunt winding is made of small-gauge wire with many turns on the coil. Since the wire is so small, the coil can have thousands of turns and still fit in the slots. The small-gauge wire cannot handle as much current as the heavy-gauge wire in the series field, but since this coil has many more turns of wire, it can still produce a very strong magnetic field. Figure 12-14 shows a picture of a DC shunt motor.

Shunt Motor Operation

A shunt motor has slightly different operating characteristics than a series motor. Since the shunt field coil is made of fine wire, it cannot produce the large current for starting like the series field. This means that the shunt motor has very low starting torque, which requires that the shaft load be rather small.

When voltage is applied to the motor, the high resistance of the shunt coil keeps the overall current flow low. The armature for the shunt motor is similar to the series motor and it will draw current to produce a magnetic field strong enough to cause the armature shaft and load to start turning. Like the series motor, when the armature begins to turn, it will produce back EMF. The back EMF will cause the current in the armature to begin to diminish to a very small level. The amount of current the armature will draw is directly related to the size of the load when the motor reaches full speed. Since the load is generally small, the armature current will be small. When the motor reaches full rpm, its speed will remain fairly constant.

Controlling the Speed

When the shunt motor reaches full rpm, its speed will remain fairly constant. The reason the speed remains constant is due to the load characteristics of the armature and shunt coil. You should remember that the speed of a series motor could not be controlled since it was totally dependent on the size of the load in comparison to the size of the motor. If the load was very large for the motor size, the speed of the armature would be very slow. If the load was light compared to the motor, the armature shaft speed would be much faster, and if no load was present on the shaft, the motor could run away.

The shunt motor's speed can be controlled. The ability of the motor to maintain a set rpm at high speed when the load changes is due to the characteristic of the shunt field and armature. Since the armature begins to produce back EMF as soon as it starts to rotate, it will use the back EMF to maintain its rpm at high speed. If the load increases slightly and causes the armature shaft to slow down, less back EMF will be produced. This will allow the difference between the back EMF and applied voltage to become larger, which will cause more current to flow. The extra current provides the motor with the extra torque required to regain its rpm when this load is increased slightly.

The shunt motor's speed can be varied in two different ways. These include varying the amount of current supplied to the shunt field and controlling the amount of current supplied to the armature. Controlling the current to the shunt field allows the rpm to be changed 10-20% when the motor is at full rpm.

This type of speed control regulation is accomplished by slightly increasing or decreasing the voltage applied to the field. The armature continues to have full voltage applied to it while the current to the shunt field is regulated by a rheostat that is connected in series with the shunt field. When the shunt field's current is decreased, the motor's rpm will increase slightly. When the shunt field's current is reduced, the armature must rotate faster to produce the same amount of back EMF to keep the load turning. If the shunt field current is increased slightly, the armature can rotate at a slower rpm and maintain the amount of back EMF to produce the armature current to drive the load. The field current can be adjusted with a field rheostat or an SCR current control.

The shunt motor's rpm can also be controlled by regulating the voltage that is applied to the motor armature. This means that if the motor is operated on less voltage than is shown on its data plate rating, it will run at less than full rpm. You must remember that the shunt motor's efficiency will drop off drastically when it is operated below its rated voltage. The motor will tend to overheat when it is operated below full voltage, so motor ventilation must be provided. You should

also be aware that the motor's torque is reduced when it is operated below the full voltage level.

Since the armature draws more current than the shunt field, the control resistors were much larger than those used for the field rheostat. During the 1950s and 1960s SCRs were used for this type of current control. The SCR was able to control the armature current since it was capable of controlling several hundred amperes. In Chapter 11 we provided an in-depth explanation of the DC motor drive.

Torque Characteristics

The armature's torque increases as the motor gains speed due to the fact that the shunt motor's torque is directly proportional to the armature current. When the motor is starting and speed is very low, the motor has very little torque. After the motor reaches full rpm, its torque is at its fullest potential. In fact, if the shunt field current is reduced slightly when the motor is at full rpm, the rpm will increase slightly and the motor's torque will also increase slightly. This type of automatic control makes the shunt motor a good choice for applications where constant speed is required, even though the torque will vary slightly due to changes in the load. Figure 12-15 shows the torque/speed curve for the shunt motor. From this diagram you can see that the speed of the shunt motor stays fairly constant throughout its load range and drops slightly when it is drawing the largest current.

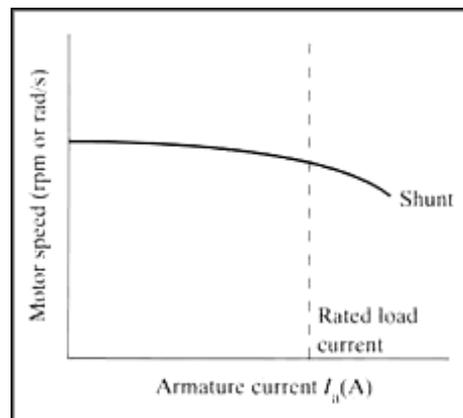


FIGURE 12-15 A curve that shows the armature current versus the armature speed for a shunt motor. Notice that the speed of a shunt motor is nearly constant.

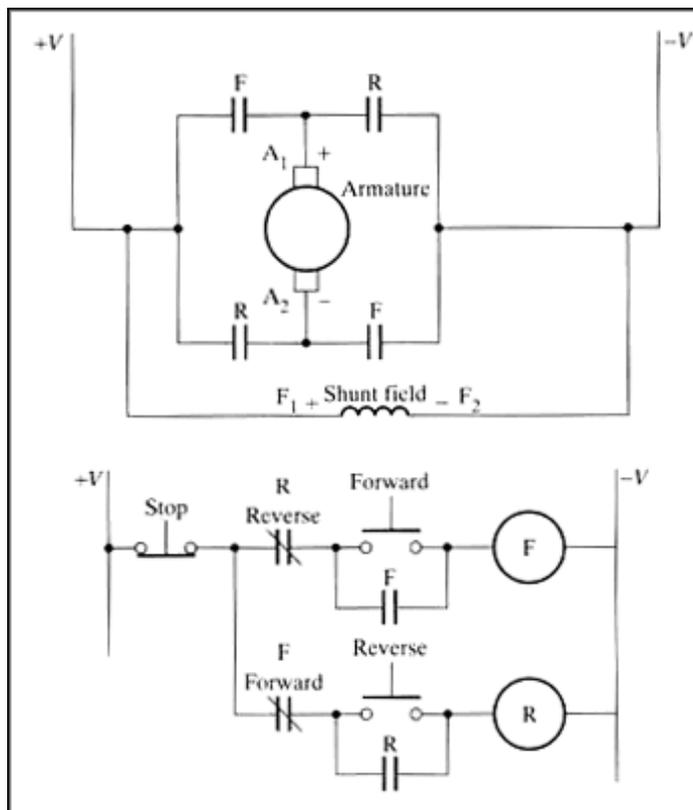


FIGURE 12-16 Diagram of a shunt motor connected to a reversing motor starter. Notice that the shunt field is connected across the armature and it is not reversed when the armature is reversed.

Reversing the Rotation

The direction of rotation of a DC shunt motor can be reversed by changing the polarity of either the armature coil or the field coil. In this application the armature coil is usually changed, as was the case with the series motor. Figure 12-16 shows the electrical diagram of a DC shunt motor connected to a forward and reversing motor starter. You should notice that the F1 and F2 terminals of the shunt field are connected directly to the power supply, and the A1 and A2 terminals of the armature winding are connected to the reversing starter. When the FMS is energized, its contacts connect the A1 lead to the positive power supply terminal and the A2 lead to the negative power supply terminal. The F1 motor lead is connected directly to the positive terminal of the power supply and the F2 lead is connected to the negative terminal. When the motor is wired in this configuration, it will begin to run in the forward direction.

When the RMS is energized, its contacts reverse the armature wires so that the A1 lead is connected to the negative power supply terminal and the A2 lead is connected to the positive power supply terminal. The field leads are connected directly to the power supply, so their polarity is not changed. Since the field's polarity has remained the same and the armature's polarity has reversed, the motor will begin to rotate in the reverse direction. The control part of the diagram shows that when the FMS coil is energized, the RMS coil is locked out.

Installing a Shunt Motor

A shunt motor can be installed easily. The motor is generally used in belt-drive applications. This means that the installation procedure should be broken into two sections, which include the mechanical installation of the motor and its load, and the installation of electrical wiring and controls.

When the mechanical part of the installation is completed, the alignment of the motor shaft and the load shaft should be checked. If the alignment is not true, the load will cause an undue stress on the armature bearing and there is the possibility of the load vibrating and causing damage to it and the motor. After the alignment is checked, the tension on the belt should also be tested. As a rule of thumb, you should have about $\sqrt{2}$ to $\frac{1}{4}$ inch of play in the belt when it is properly tensioned.

Several tension measurement devices are available to determine when a belt is tensioned properly. The belt tension can also be compared to the amount of current the motor draws. The motor must have its electrical installation completed to use this method.

The motor should be started, and if it is drawing too much current, the belt should be loosened slightly but not enough to allow the load to slip. If the belt is slipping, it can be tightened to the point where the motor is able to start successfully and not draw current over its rating.

The electrical installation can be completed before, after, or during the mechanical installation. The first step in this procedure is to locate the field and armature leads in the motor and prepare them for field connections. If the motor is connected to magnetic or manual across the line starter, the F1 field coil wire can be connected to the A1 armature lead and an interconnecting wire, which will be used to connect these leads to the T1 terminal on the motor starter. The F2 lead can be connected to the A2 lead and a second wire, which will connect these leads to the T2 motor starter terminal.

When these connections are completed, field and armature leads should be replaced back into the motor and the field wiring cover or motor access plate should be replaced. Next the DC power supply's positive and negative leads should be connected to the motor starter's L1 and L2 terminals, respectively.

After all of the load wires are connected, any pilot devices or control circuitry should be installed and connected. The control circuit should be tested with the load voltage disconnected from the motor. If the control circuit uses the same power source as the motor, the load circuit can be isolated so the motor will not try to start by disconnecting the wire at terminal L2 on the motor starter. Operate the control circuit several times to ensure that it is wired correctly and operating properly. After you have tested the control circuit, the lead can be replaced to the L2 terminal of the motor starter and the motor can be started and tested for proper operation. Be sure to check the motor's voltage and current while it is under load to ensure that it is operating correctly. It is also important to check the motor's temperature periodically until you are satisfied the motor is operating correctly.

If the motor is connected to a reversing starter or reduced-voltage starting circuit, their operation should also be tested. You may need to read the material in Section 15.3.6 to fully understand the operation of these methods of starting the motor using reduced-voltage methods. If the motor is not operating correctly or develops a fault, a troubleshooting procedure should be used to test the motor and locate the problem.

Troubleshooting

When a DC shunt motor develops a fault, you must be able to locate the problem quickly and return the motor to service or have it replaced. The most likely problems to occur with the shunt motor include loss of supply voltage or an open in either the shunt winding or the armature winding. Other problems may arise that cause the motor to run abnormally hot even though it continues to drive the load. The motor will show different symptoms for each of these problems, which will make the troubleshooting procedure easier.

When you are called to troubleshoot the shunt motor, it is important to determine if the problem occurs while the motor is running or when it is trying to start. If the motor will not start, you should listen to see if the motor is humming and trying to start. When the supply voltage has been interrupted due to a blown fuse or a de-energized control circuit, the motor will not be able to draw any current and it will be silent when you try to start it. You can also determine that the supply voltage has been lost by measuring it with a voltmeter at the starter's L1 and L2 terminals. If no voltage is present at the load terminals, you should check for voltage at the starter's T1 and T2 terminals. If voltage is present here but not at the load terminals, it indicates that the motor starter is de-energized or defective. If no voltage is present at the T1 and T2 terminals, it indicates that supply voltage has been lost prior to the motor starter. You will need to check the supply fuses and the rest of the supply circuit to locate the fault.

If the motor tries to start and hums loudly, it indicates that the supply voltage is present. The problem in this case is probably due to an open field winding or armature winding. It could also be caused by the supply voltage being too low.

The most likely problem will be an open in the field winding since it is made from small-gauge wire. The open can occur if the field winding draws too much current or develops a short circuit between the insulation in the coils. The best way to test the field is to remove supply voltage to the motor by opening the disconnect or de-energizing the motor starter. Be sure to use a *lockout* when you are working on the motor after the disconnect has been opened. The lockout is a device that is placed on the handle of the disconnect after the handle is placed in the off position, and it allows a padlock to be placed around it so it cannot be removed until the technician has completed the work on the circuit. If lockout has extra holes, additional padlocks can be placed on it by other technicians who are also working on this system. This ensures that the power cannot be returned to the system until all technicians have removed their padlocks. The lockout will be explained in detail in the chapter on motor controls later in this text.

After power has been removed, the field terminals should be isolated from the armature coil. This can be accomplished by disconnecting one set of leads where the field and armature are connected together. Remember that the field and armature are connected in parallel and if they are not isolated, your continuity test will show a completed circuit even if one of the two windings has an open.

When you have the field coil isolated from the armature coil, you can proceed with the continuity test. Be sure to use the R X 1k or R X 10k setting on the ohmmeter because the resistance in the field coil will be very high since the field coil may be wound from several thousand feet of wire. If the field winding test indicates the field winding is good, you should continue the procedure and test the armature winding for continuity.

The armature winding test may show that an open has developed from the coil burning open or from a problem with the brushes. Since the brushes may be part of the fault, they should be visually inspected and replaced if they are worn or not seating properly. If the commutator is also damaged, the armature should be removed, so the commutator can be turned down on a lathe.

If either the field winding or the armature winding has developed an open circuit, the motor will have to be removed and replaced. In some larger motors it will be possible to change the armature by itself rather than remove and replace the entire motor. If the motor operates but draws excessive current or heats up, the motor should be tested for loose or shorting coils. Field coils may tend to come loose and cause the motor to vibrate and overheat, or the armature coils may come loose from their slots and cause problems. If the motor continues to overheat or operate roughly, the motor should be removed and sent to a motor rebuilding shop so that a more in-depth test may be performed to find the problem before the motor is permanently damaged by the heat.

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Selecting a Servomotor for an Application
by Thomas E. Kissell
Industrial Electronics, Second Edition, Prentice Hall PTR

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The conversion of ounce-inches, pound-inches, and newton-meters follows:

- 1 lb-in. = 16 oz-in.
- 1 lb-in. = 0.112085 N·m

The rated power for each motor is listed in horsepower (hp) and kilowatts (kW). The calculation for determining horsepower and the conversion from horsepower to watts follows.

- Horsepower = (torque x speed)/16,800
- Torque = oz-in.
- Speed = revolutions per second

The horsepower calculation uses the torque available at the specified speed.

1 hp = 746 Watts

The rated speed is listed on the data table as rpm (revolutions per minute). The rated current is listed in A rms. The peak current and the maximum continuous AC input power are listed in A rms. The rotor inertia is rated in oz-in.² (mass). The model numbers for each motor are listed across the top of this table.

Technical Data		Z-605 ZX-605 ZXF-605	Z-606 ZX-606 ZXF-606	Z-610 ZX-610 ZXF-610	Z-620 ZX-620 ZXF-620	Z-630 ZX-630 ZXF-630	Z-635 ZX-635 ZXF-635	Z-640 ZX-640 ZXF-640	Z-910 ZX-910 ZXF-910	Z-920 ZX-920 ZXF-920	Z-930 ZX-930 ZXF-930	Z-940 ZX-940 ZXF-940
Continuous stall torque	oz-in	346	633	867	1,743	2,475	2,475	4,114	2,407	4,263	5,990	9,021
	lb-in	22	40	54	109	155	155	257	150	266	374	564
	Nm	2.44	4.47	6.12	12.31	17.48	17.48	29.05	17.0	30.1	42.3	63.7
Peak torque	oz-in	1,083	1,954	1,733	3,486	4,951	4,951	8,228	5,205	8,525	11,980	18,041
	lb-in	68	122	108	218	309	309	514	325	533	749	1,128
	Nm	7.65	13.80	12.24	24.62	34.96	34.96	58.10	35.4	61.5	84.6	127.5
Rated power	hp	2	2.1	4.2	5.6	5.4	6.1	5.9	9.6	10.4	11.0	11.1
	k Watts	1.49	1.57	3.13	4.18	4.03	4.5	4.40	7.2	7.8	8.2	8.3
Rated speed	rpm	6,200	3,600	7,000	3,700	2,500	3,000	1,600	5,000	3,150	2,300	1,500
	rps	103	60	117	62	42	50	27	83.3	52.5	38.3	25.0
Rated current (line)	A (rms)	5	5.3	14.1	14.1	14.1	14.1	14.1	27.2	27.7	28.3	28.3
Peak current (3.3 sec max)	A (rms)	16.6	17.2	28.2	28.2	28.2	28.2	28.2	56.6	56.6	56.6	56.6
Max cont AC A (rms) input power (3 phase 240 VAC)	A (rms)	6	6	15	15	15	15	15	30	30	30	30
Rotor inertia	oz-in ² (mass)	5.45	9.45	13.73	35.87	50.79	56.21	111.21	50.79	111.21	166.21	459.48
	oz-in-sec ²	0.01	0.02	0.04	0.09	0.13	0.15	0.29	0.132	0.288	0.431	1.190
	kgm ² x10 ⁶	99.6	172.9	251.2	656	929	1,028	2,034	929	2,034	3,040	8,404
Motor weight	lbs	10.0	14.0	17.0	29.0	32.0	37	51.0	32.0	57.0	65.0	112.0
	kg	4.5	6.4	7.7	13.2	14.5	16.8	23.2	15.0	26.0	29.0	51.0

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Servomotor Overview

by Thomas E. Kissell

Industrial Electronics, Second Edition, Prentice Hall PTR

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- Brushless Servomotors

Introduction

Servomotors are available as AC or DC motors. Early servomotors were generally DC motors because the only type of control for large currents was through SCRs for many years. As transistors became capable of controlling larger currents and switching the large currents at higher frequencies, the AC servomotor became used more often. Early servomotors were specifically designed for servo amplifiers. Today a class of motors is designed for applications that may use a servo amplifier or a variable-frequency controller, which means that a motor may be used in a servo system in one application, and used in a variable-frequency drive in another application. Some companies also call any closed-loop system that does not use a stepper motor a servo system, so it is possible for a simple AC induction motor that is connected to a velocity controller to be called a servomotor.

Some changes that must be made to any motor that is designed as a servomotor includes the ability to operate at a range of speeds without overheating, the ability to operate at zero speed and retain sufficient torque to hold a load in position, and the ability to operate at very low speeds for long periods of time without overheating. Older-type motors have cooling fans that are connected directly to the motor shaft. When the motor runs at slow speed, the fan does not move enough air to cool the motor. Newer motors have a separate fan mounted so it will provide optimum cooling air. This fan is powered by a constant voltage source so that it will turn at maximum RPM at all times regardless of the speed of the servomotor. One of the most usable types of motors in servo systems is the permanent magnet (PM) type motor. The voltage for the field winding of the permanent magnet type motor can be AC voltage or DC voltage. The permanent magnet-type motor is similar to other PM type motors presented previously. Figure 11-83 shows a cutaway picture of a PM motor and Fig. 11-84 shows a cutaway diagram of a PM motor. From the picture and diagram you can see the housing, rotor and stator all look very similar to the previous type PM motors. The major difference with this type of motor is that it may have gear reduction to be able to move larger loads quickly from a stand still position. This type of PM motor also has an encoder or resolver built into the motor housing. This ensures that the device will accurately indicate the position or velocity of the motor shaft.

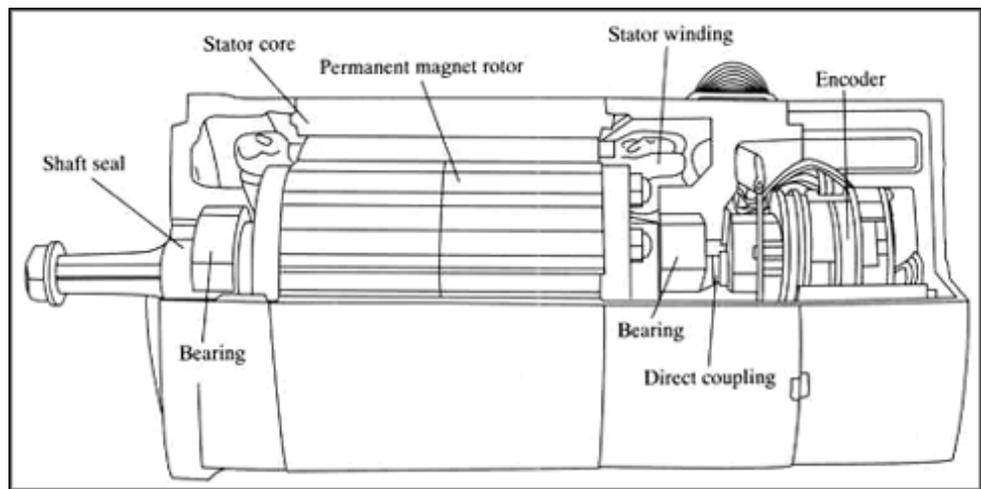


FIGURE 11-83 Typical PM servomotors. (Courtesy of Pacific Scientific.)

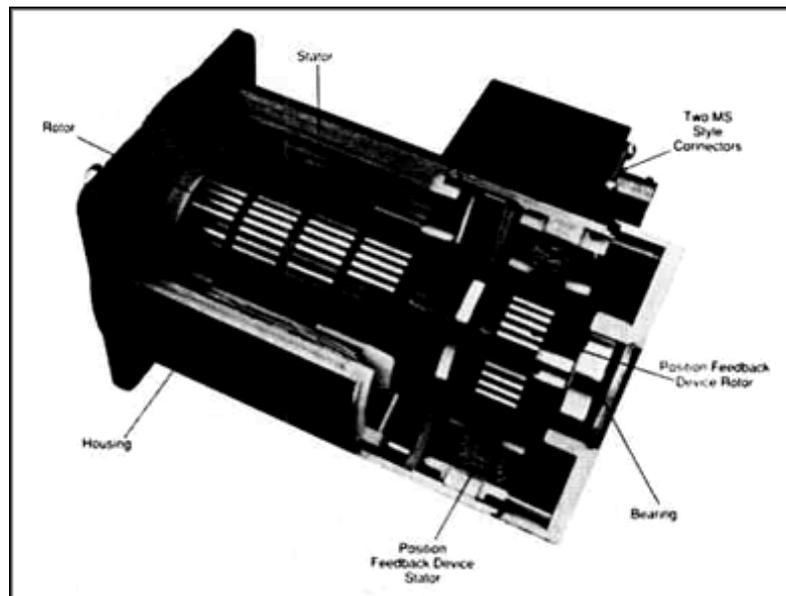


FIGURE 11-84 Cutaway picture of a permanent magnet servomotor. (Courtesy of Pacific Scientific.)

Brushless Servomotors

The brushless servomotor is designed to operate without brushes. This means that the commutation that the brushes provided must now be provided electronically. Electronic commutation is provided by switching transistors on and off at appropriate times. Figure 11-85 shows three examples of the voltage and current waveforms that are sent to the brushless servomotor. Figure 11-86 shows an example of the three windings of the brushless servomotor. The main point about the brushless servomotor is that it can be powered by either ac voltage or dc voltage.

Figure 11-85 shows three types of voltage waveforms that can be used to power the brushless servomotor. Figure 11-85a shows a trapezoidal EMF (voltage) input and a square wave current input. Figure 11-85b shows a sinusoidal waveform for the input voltage and a square wave current waveform. Figure 11-85c shows a sinusoidal input waveform and a sinusoidal current waveform. The sinusoidal input and sinusoidal current waveform are the most popular voltage supplies for the brushless servomotor.

Figure 11-86 shows three sets of transistors that are similar to the transistors in the output stage of the variable-frequency drive. In Fig. 11-86a the transistors are connected to the three windings of the motor in a similar manner as in the variable-frequency drive. In Fig. 11-86b the diagram of the waveforms for the output of the transistors is shown as three separate sinusoidal waves. The waveforms for the control circuit for the base of each transistor are shown in Fig. 11-86c. Figure 11-86d shows the back EMF for the drive waveforms.

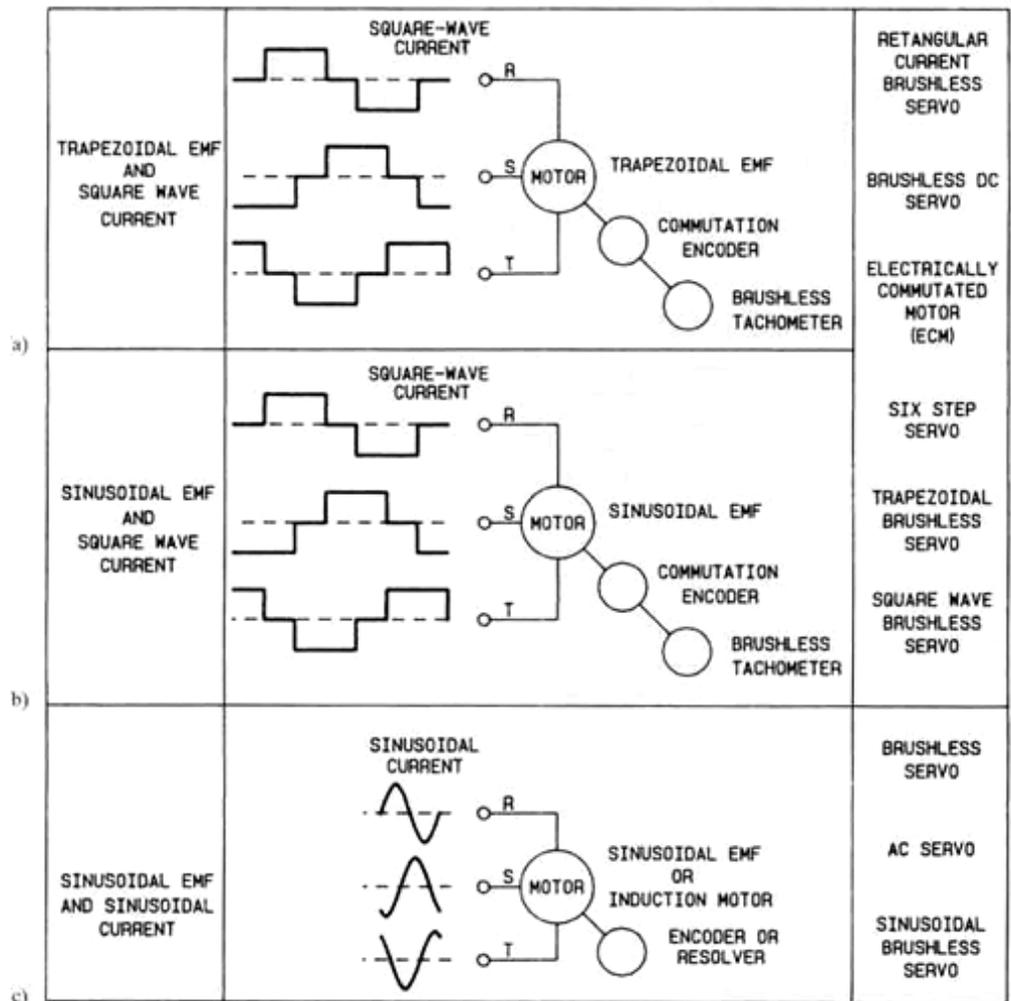


FIGURE 11-85 (a) Trapezoidal input voltage and square wave current waveforms. (b) Sinusoidal input voltage and sinusoidal voltage and square wave output voltage waveforms. (c) Sinusoidal input voltage and sinusoidal current waveforms. This has become the most popular type of brushless servomotor control. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

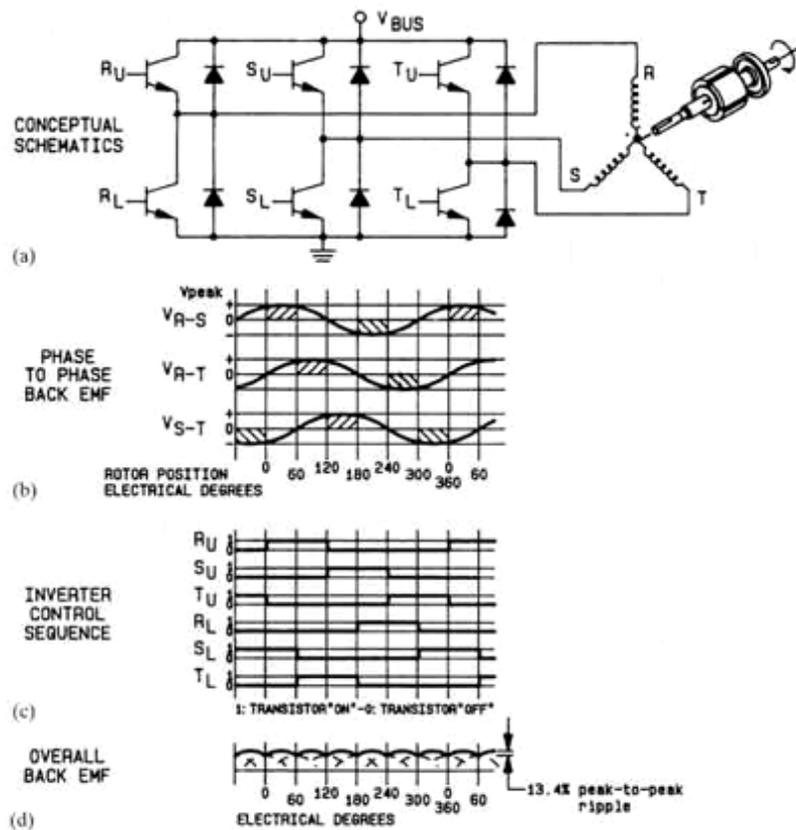


FIGURE 11-86 (a) Transistors connected to the three windings of the brushless servomotor. (b) Waveforms of the three separate voltages that are used to power the three motor windings. (c) Waveforms of the signals used to control the transistor sequence that provides the waveforms for the previous diagram, (d) Waveform of the overall back EMF. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

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Servomotors

by Thomas E. Kissell

Industrial Electronics, Prentice Hall PTR

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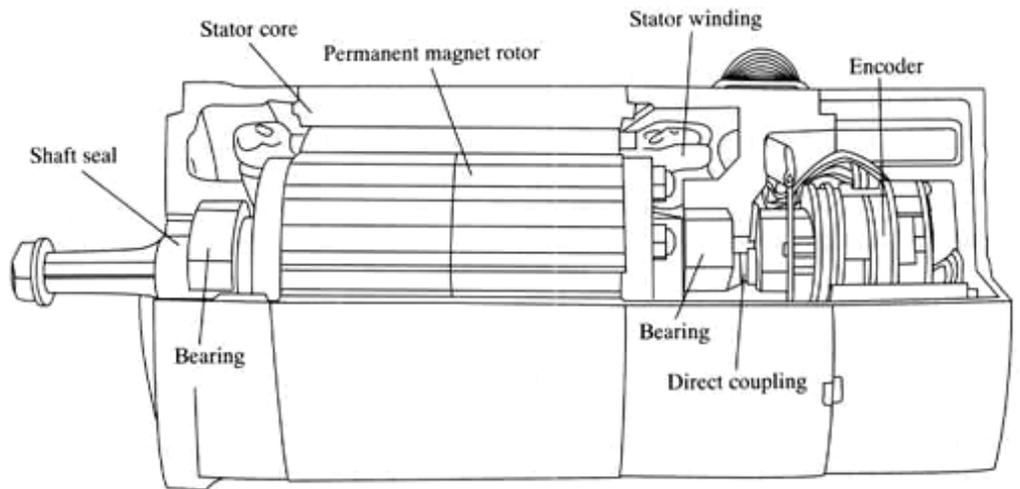


FIGURE 11-83 Typical PM servomotors. (Cour-tesy of Pacific Scientific.)

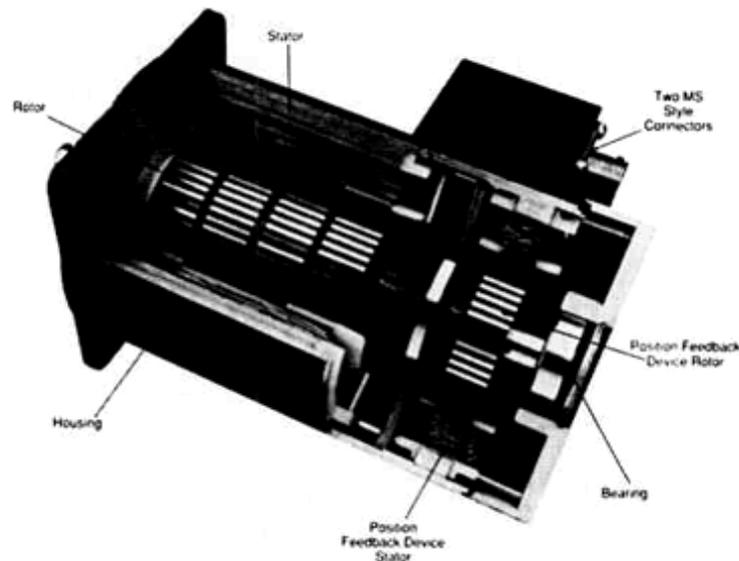


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11.11.5.1 Brushless Servomotors The brushless servomotor is designed to operate without brushes. This means that the commutation that the brushes provided must now be provided electronically. Electronic commutation is provided by switching transistors on and off at appropriate times. Figure 11-85 shows three examples of the voltage and current waveforms that are sent to the brushless servomotor. Figure 11-86 shows an example of the three windings of the brushless servomotor. The main point about the brushless servomotor is that it can be powered by either ac voltage or dc voltage.

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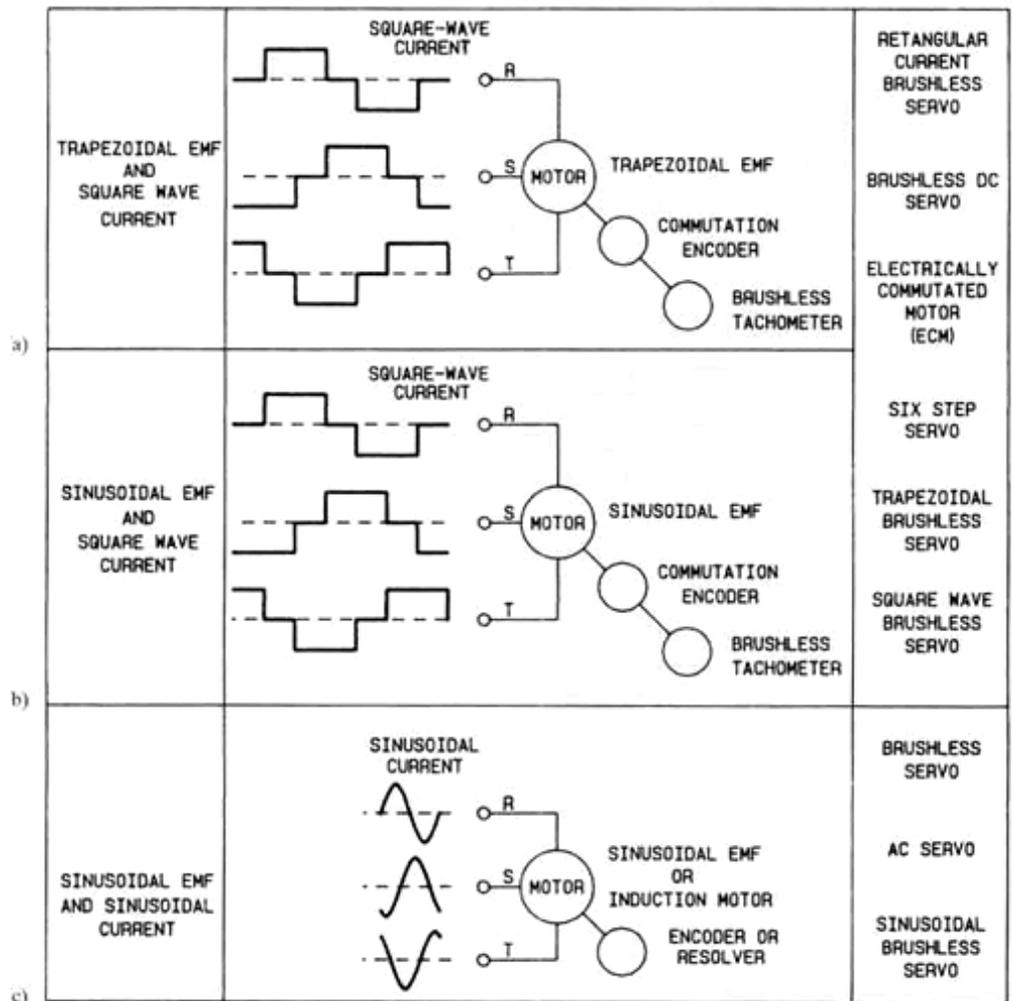


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Servomotor Controllers

Servomotor controllers have become more than just amplifiers for a servomotor. Today servomotor controllers must be able to make a number of decisions and provide a means to receive signals from external sensors and controls in the system, and send signals to host controllers and PLCs that may interface with the servo system. Figure 11-87 shows a picture of several servomotors and their amplifiers. The components in this picture look similar to a variety of other types of motors and controllers.

Figure 11-88 shows a diagram of the servomotor controller so that you can see some of the differences from other types of motor controllers. The controller in this diagram is for a DC servomotor. The controller has three ports that bring signals in or send signals out of the controller. The power supply, servomotor, and tachometer are connected to port P3 at the bottom of the controller. You can see that the supply voltage is 115-volt AC single phase. A main disconnect is connected in series with the LI wire. The LI and N lines supply power to an isolation step-down transformer. The secondary voltage of the trans-former can be any voltage between 20 and 85 volts. The controller is grounded at terminal 8. You should remember that the ground at this point is only used to provide protection against short circuits for all metal parts in the system. The servomotor is connected to the controller at terminals 4 and 5. Terminal 5 is + and terminal 4 is -. Terminal 3 provides a ground for the shield of the wires that connect the motor and the controller. The tachometer is connected to terminals 1 and 2. Terminal 2 is + and terminal 1 is -. The shield for this cable is grounded to the motor case. The wires connected to this port will be larger than wires connected to the other ports, since they must be capable of carrying the larger motor current. If the motor uses an external cooling fan, it will be connected through this port. In most cases the cooling fan will be powered by single-phase or three-phase AC voltage that remains at a constant level, such as 110 volts AC or 240 volts AC.

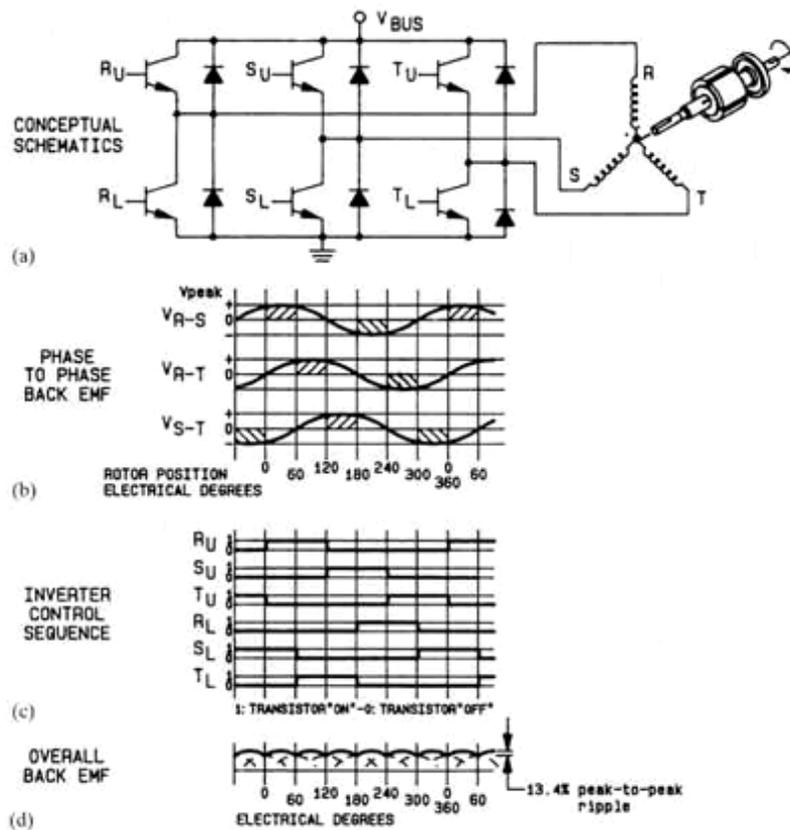


FIGURE 11-86 (a) Transistors connected to the three windings of the brushless servomotor. (b) Waveforms of the three separate voltages that are used to power the three motor windings. (c) Waveforms of the signals used to control the transistor sequence that provides the waveforms for the previous diagram, (d) Waveform of the overall back EMF. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

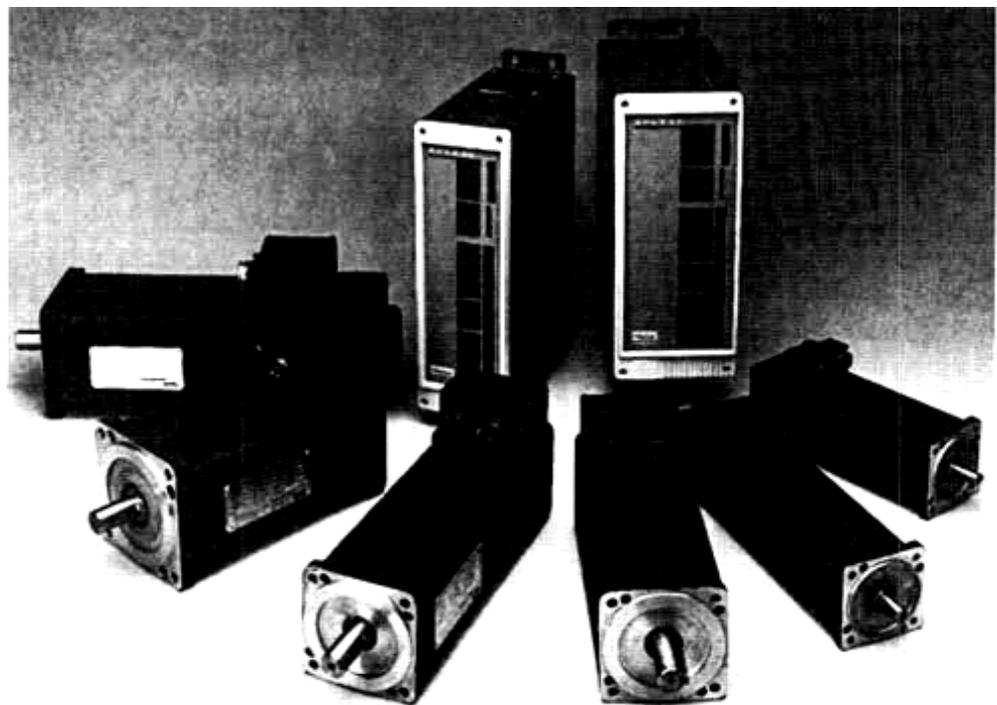


FIGURE 11-87 Example servomotors and amplifiers. (Courtesy of Pacific Scientific.)

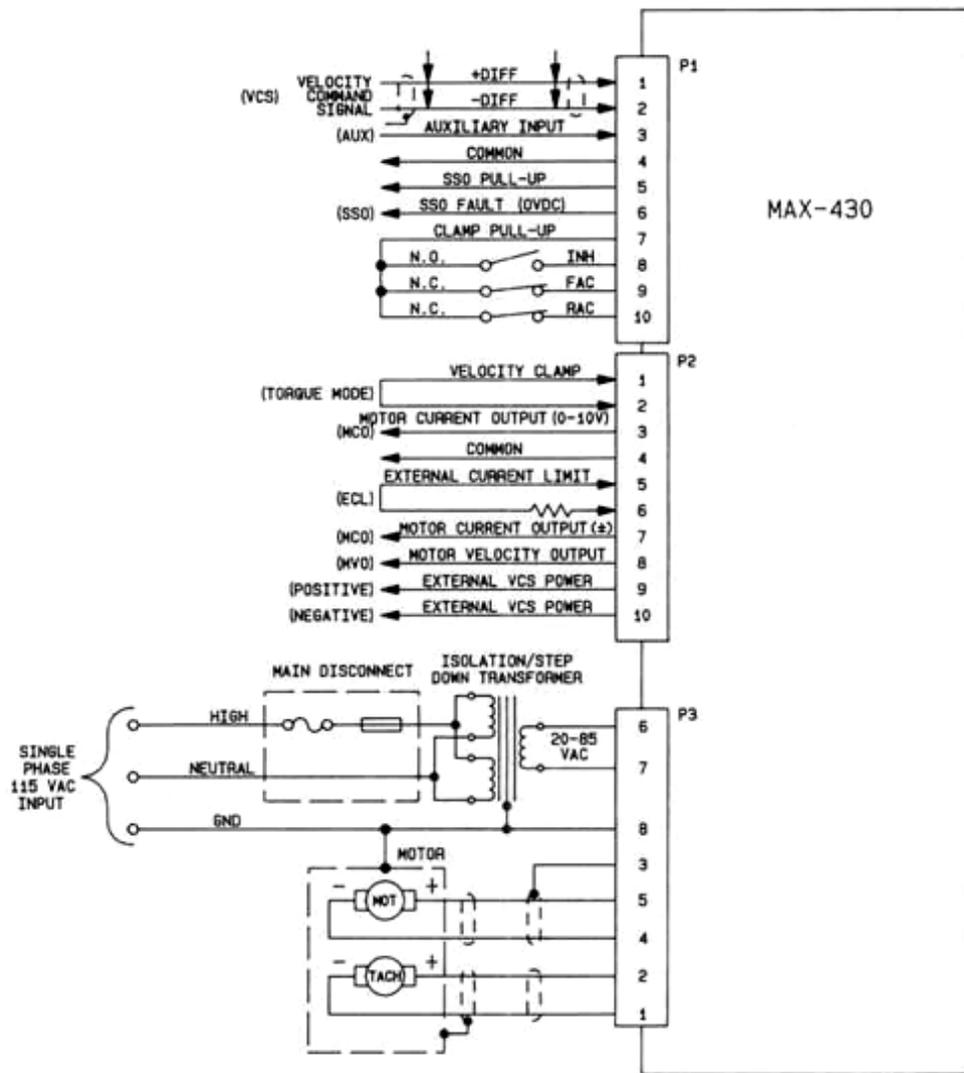


FIGURE 11-88 Diagram of a servo controller. This diagram shows the digital (on-off) signals and the analog signals that are sent to the controller, and the signals the controller sends back to the host controller or PLC. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

The command signal is sent to the controller through port P1. The terminals for the command signal are 1 and 2. Terminal 1 is + and terminal 2 is -. This signal is a type signal, which means that it is not grounded or does not share a ground potential with any other part of the circuit. Several additional auxiliary signals are also connected through port 1. These signals include inhibit (INH), which is used to disable the drive from an external controller, and forward and reverse commands (FAC and RAC), which tell the controller to send the voltage to the motor so that it will rotate in the forward or reverse direction. In some applications, the forward maximum travel limit switch and reverse maximum travel limit switch are connected so that if the machine travel moves to the extreme position so that it touches the overtravel limit switch, it will automatically energize the drive to begin travel in the opposite direction.

Port P1 also provides several digital output signals that can be used to send fault signals or other information such as "drive running" back to a host controller or PLC. Port P1 basically is the interface for all digital (on-off) signals.

Port P2 is the interface for analog (0-max) signals. Typical signals on this bus include motor current and motor velocity signals that are sent from the servo controller back to the host or PLC where they can be used in verification logic to ensure the controller is sending the correct information to the motor. Input signals from the host or PLC can also be sent to the controller to set maximum current and velocity for the drive. In newer digital drives, these values are controlled by *drive parameters* that are programmed into the drive.

PWM Servo Amplifier

The PWM servo amplifier is used on small-size servo applications that use DC brush-type servomotors. Figure 11-89 shows a diagram for this type of amplifier. From the diagram you can see that single-phase AC power is provided to the amplifier as the supply at the lower left part of the diagram. The AC voltage is rectified and sent to the output section of the drive that is shown in the top right corner of the diagram. The output section of the drive uses four IGBTs to create the pulse-width modulation waveform. The IGBTs are connected so that they provide 30-120 volts DC and up to 30 A to the brush-type DC servo-motor. The polarity of the motor is indicated in the diagram.

The remaining circuits show a variety of fault circuits in the middle of the diagram that originate from the *fault logic board* and provide an output signal at the bottom of the diagram. You should notice that the fault output signals include overvoltage, overtemperature, and overcurrent. A fourth signal is identified as SSO (system status output), which indicates the status of the system as faulted anytime a fault has occurred. A jumper is used to set the SSO signal as an open collector output with a logic level "1" indicating the drive is ready, or as a normally closed relay indicating the drive is ready.

The input terminals at the bottom right part of the diagram are used to *enable* or *inhibit* the drive, and to select forward amplifier clamp (FAC) or reverse amplifier clamp (RAC). The inhibit signal is used as a control signal, since it inhibits the output stage of the amplifier if it is high. The FAC and RAC signals limit the current in the opposite direction to 5%.

The input signals are shown in the diagram at the upper left side. The VCS (velocity command signal) requires a +VCS and a -VCS signal to provide the differential signal.

Applications for Servo Amplifiers and Motors

You will get a better idea of how servomotors and amplifiers operate if you see some typical applications. Figure 11-90 shows an example of a servomotor used to control a press feed. In this application sheet material is fed into a press where it is cut off to length with a knife blade or shear. The sheet material may have a logo or other advertisement that must line up registration marks with the cut-off point. In this application the speed and position of the sheet material must be synchronized with the correct cut-off point. The feedback sensor could be an encoder or resolver that is coupled with a photoelectric sensor to determine the location of the registration mark. An operator panel is provided so that the operator can jog the system for maintenance to the blades, or when loading a new roll of material. The operator panel could also be used to call up parameters for the drive that correspond to each type of material that is used. The system could also be integrated with a programmable controller or other type of controller and the operator panel could be used to select the correct cutoff points for each type of material or product that is run.

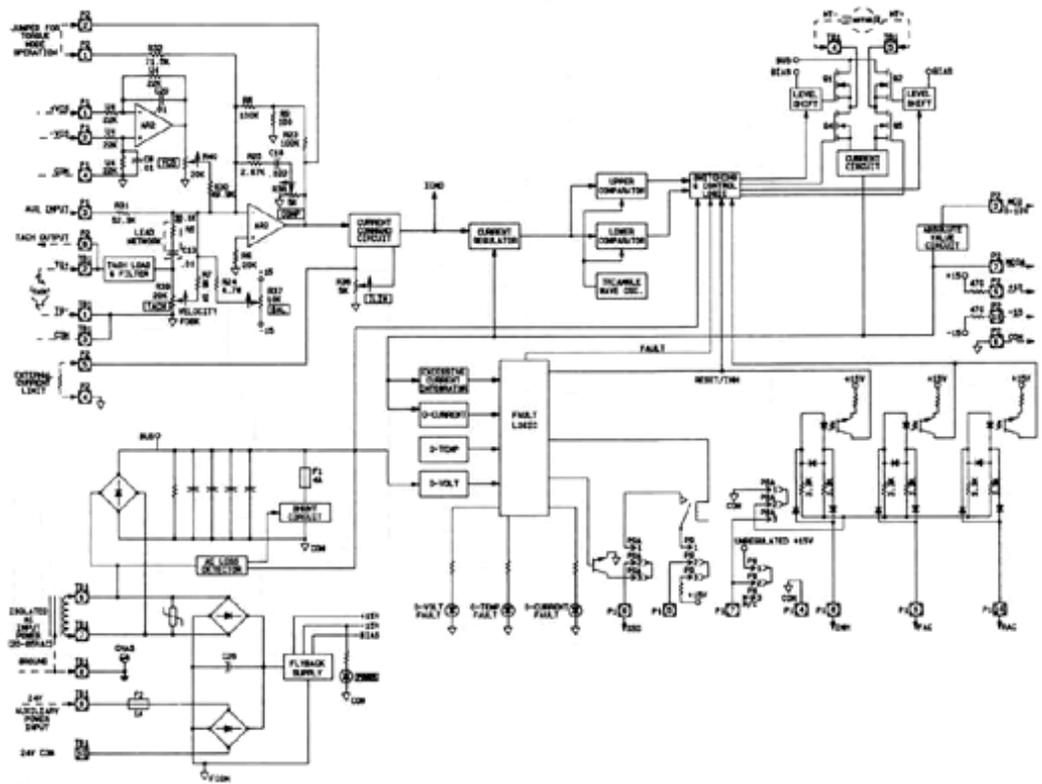
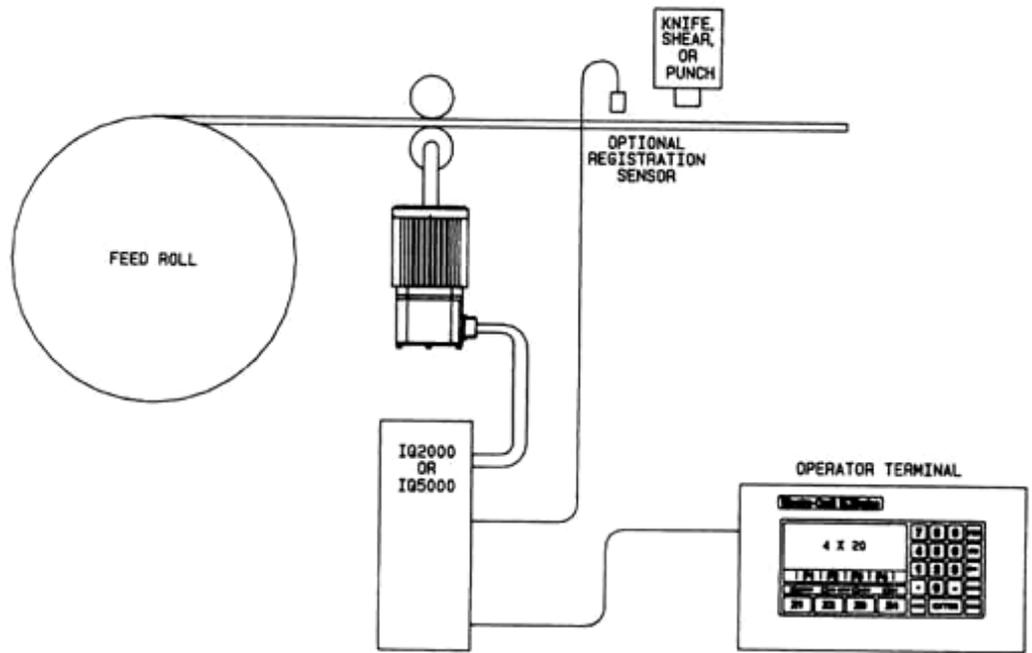


FIGURE 11-89 Diagram of a pulse-width modulator (PWM) amplifier with a brush-type DC servomotor. (Courtesy of Electro-Craft, A Rockwell Automation Business.)



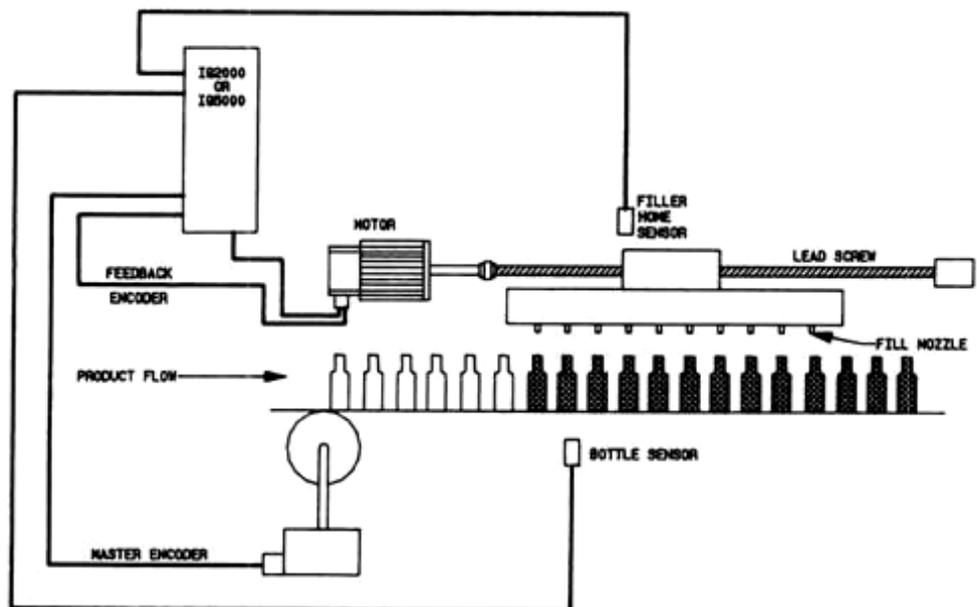
PRESS FEED APPLICATION

FIGURE 11-90 Application of a servomotor controlling the speed of material as it enters a press for cutting pieces to size. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

11.11.8.1 An Example of a Servo Controlled In-Line Bottle-Filling Application

A second application is shown in Fig. 11-91. In this application multiple filling heads line up with bottles as they move along a continuous line. Each of the filling heads must match up with a bottle and track the bottle while it is moving. Product is dispensed as the nozzles move with the bottles. In this application 10 nozzles are mounted on a carriage that is driven by a ball-screw mechanism. The ball-screw mechanism is also called a lead screw. When the motor turns the shaft of the ball screw, the carriage will move horizontally along the length of the ball-screw shaft. This movement will be smooth so that each of the nozzles can dispense product into the bottles with little spillage.

The servo drive system utilizes a positioning drive controller with software that allows the position and velocity to be tracked as the conveyor line moves the bottles. A master encoder tracks the bottles as they move along the conveyor line. An auger feed system is also used just prior to the point where the bottles enter the filling station. The auger causes a specific amount of space to be set between each bottle as it enters the filling station. The bottles may be packed tightly as they approach the auger, but as they pass through the auger their space is set exactly so that the necks of the bottles will match the spacing of the filling nozzles. A detector is also in conjunction with the dispensing system to ensure that no product is dispensed from a nozzle if a bottle is missing or large spaces appear between bottles.



BOTTLE FILLING MACHINE

FIGURE 11-91 Application of a beverage-filling station controlled by a servomotor. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

The servo drive system compares the position of the bottles from the master encoder to the feedback signal that indicates the position of the filling carriage that is mounted to the ball screw. The servo drive amplifier will increase or decrease the speed of the ball-screw mechanism so that the nozzles will match the speed of the bottles exactly.

11.11.8.2 An Example of a Servo Controlled Precision Auger Filling System

A third application for a servo system is provided in Fig. 11-92. In this application a large filling tank is used to fill containers as they pass along a conveyor line. The material that is dispensed into the containers can be a single material fill or it can be one of several materials added to a container that is dumped into a mixer for a blending operation. Since the amount of material that is dispensed into the container must be accurately weighed and metered into the box, an auger that is controlled by a servo system is used. The feedback sensor for this system can be a weighing system such as the load cell discussed in earlier chapters. The command signal can come from a programmable controller or the operator can enter it manually by selecting a recipe from the operator's terminal. The amount of material can be different from recipe to recipe.

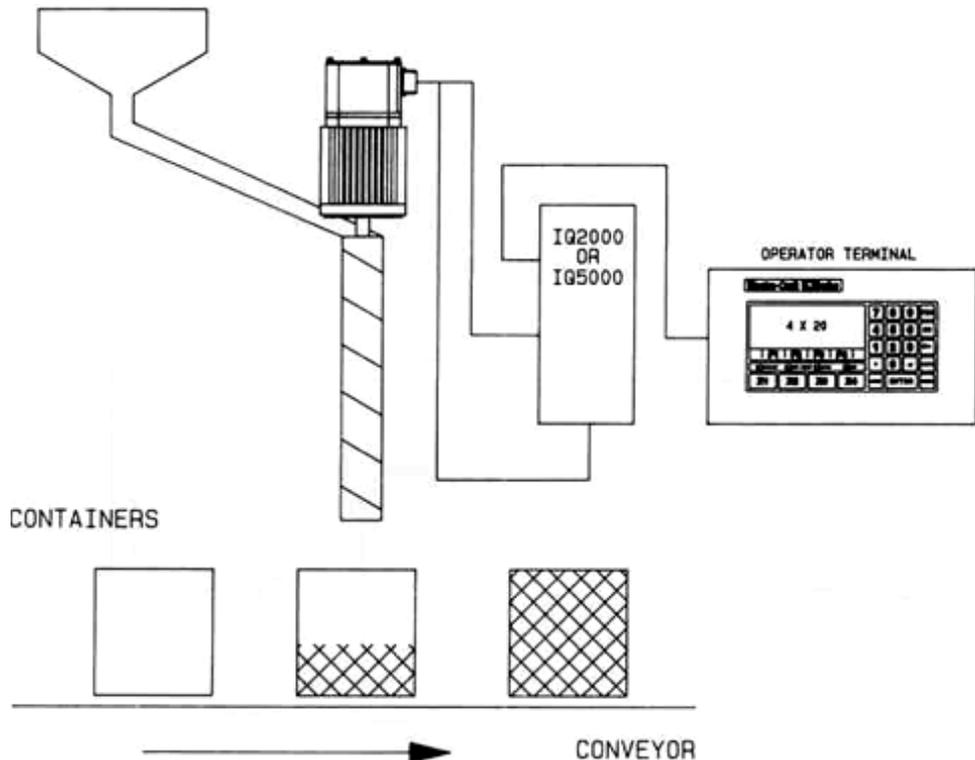


FIGURE 11-92 Application of a precision auger filling station controlled by a servomotor. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

The speed of the auger can be adjusted so that it runs at high speed when the container is first being filled, and the speed can be slowed to a point where the final grams of material can be metered precisely as the container is filled to the proper point. As the price of material increases, precision filling equipment can provide savings as well as quality in the amount of product used in the recipe.

11.11.8.3 An Example of a Label Application Using Servomotors

The fourth application has a servomotor controlling the speed of a label-feed mechanism that pulls preprinted labels from a roll and applies them to packages as they move on a continuous conveyor system past the labeling mechanism. The feedback signals are provided by an encoder that indicates the location of the conveyor, tach generator that indicates the speed of the conveyor, and a sensor that indicates the registration mark on each label. The servo positioning system is controlled by a microprocessor that sets the error signal, and the servo amplifier that provides power signals to the servomotor. This application is shown in Fig. 11-93.

11.11.8.4 An Example of a Random Timing Infeed System Controlled by a Servomotor

The fifth application is presented in Fig. 11-94, and it shows a series of packaging equipment that operates as three separate machines. The timing cycle of each station of the packaging system is independent from the others. The packaging system consists of an *infeed conveyor*, a *positioning conveyor*, and a *wrapping station*. The infeed conveyor and the wrapping station are mechanically connected so that they run at the same speed. The position of the packages on the wrapping station must be strictly controlled so that the packages do not become too close to each other. A piece of metal called a *flight* is connected to the wrapping station conveyor at specific points to ensure each package stays in position. A sensor is mounted at the beginning of the positioning conveyor to determine the front edge of the package when it starts to move onto the positioning conveyor. A second sensor is positioned at the bottom of the packaging conveyor to detect the flights. Both of

these signals from the sensors are sent to the servomotor to provide information so the servo can adjust the speed of the positioning conveyor so that each package aligns with one of the flights as it moves onto the packaging conveyor. This application shows that the servo positioning controller can handle a variety of different signals from more than one sensor because the controller uses a microprocessor.

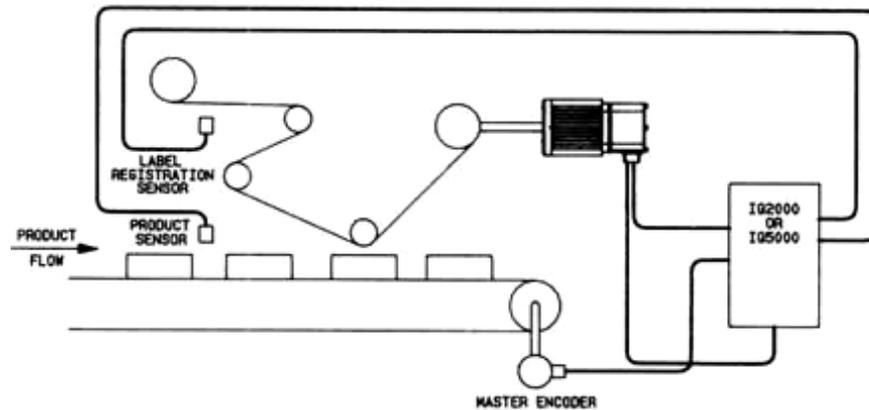


FIGURE 11-93 Example of a labeling application controlled by a servomotor. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

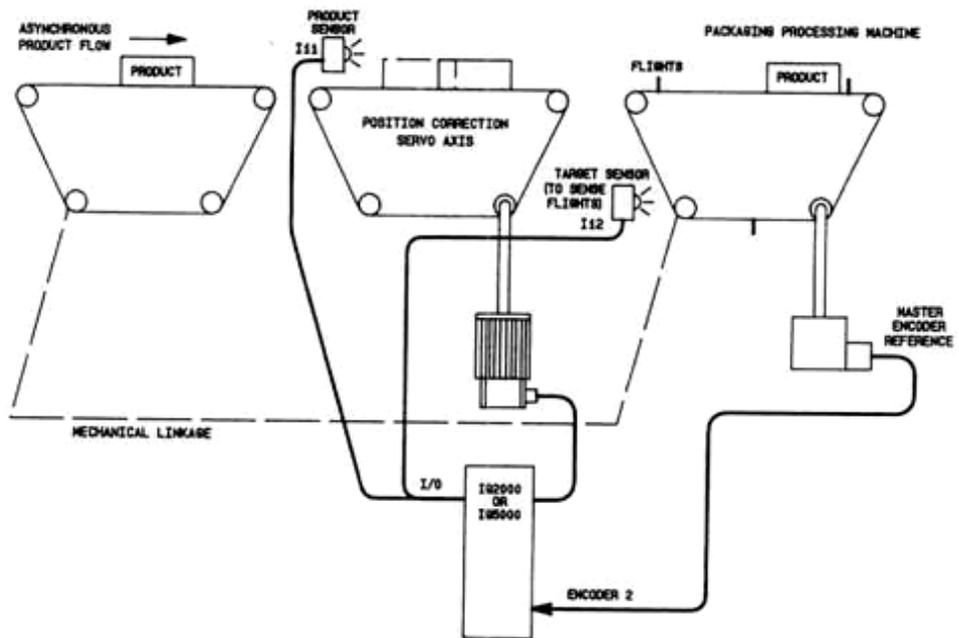


FIGURE 11-94 Example of a packaging system with random timing functions controlled by a servomotor. (Courtesy of Electro-Craft, A Rockwell Automation Business.)

Selecting a Servomotor for an Application

When you must select a servomotor for initial installation or for a replacement, you will need to consider the following data, which are shown in the table in Fig. 11-95. The first point to consider is whether the motor will be used for continuous duty or intermittent duty. The table shows the amount of continuous stall torque each motor can produce. The second rating from the table is the amount of peak torque. Both the continuous torque and the peak torque are listed in ounce-inches (oz-in.), pound-inches (lb-in.), or inch-pound (in-lb.), and in newton-meters (N-m).

The conversion of ounce-inches, pound-inches, and newton-meters follows:

The rated power for each motor is listed in horsepower (hp) and kilowatts (kW). The calculation for determining horsepower and the conversion from horsepower to watts follows.

The horsepower calculation uses the torque available at the specified speed.

The rated speed is listed on the data table as rpm (revolutions per minute). The rated current is listed in A rms. The peak current and the maximum continuous AC input power are listed in A rms. The rotor inertia is rated in oz-in.² (mass). The model numbers for each motor are listed across the top of this table.

Technical	Data	Z-605 ZX-605 ZXF-605	Z-606 ZX-606 ZXF-606	Z-610 ZX-610 ZXF-610	Z-620 ZX-620 ZXF-620	Z-630 ZX-630 ZXF-630	Z-635 ZX-635 ZXF-635	Z-640 ZX-640 ZXF-640	Z-910 ZX-910 ZXF-910	Z-920 ZX-920 ZXF-920	Z-930 ZX-930 ZXF-930	Z-940 ZX-940 ZXF-940
Continuous stall torque oz-in lb-in Nm	346 22 2.44	633 40 4.47	867 54 6.12	1,743 109 12.31	2,475 155 17.48	2,475 155 17.48	4,114 257 29.05	2,407 150 17.0	4,263 266 30.1	5,990 374 42.3	9,021 564 63.7	
Peak torque	oz-in lb-in Nm	1,083 68 7.65	1,954 122 13.80	1,733 108 12.24	3,486 218 24.62	4,951 309 34.96	4,951 309 34.96	8,228 514 58.10	5,205 325 35.4	8,525 533 61.5	11,980 749 84.6	18,041 1,128 127.5
Rated power	hp k Watts	2 1.49	2.1 1.57	4.2 3.13	5.6 4.18	5.4 4.03	6.1 4.5	5.9 4.40	9.6 7.2	10.4 7.8	11.0 8.2	11.1 8.3
Rated speed	rpm rps	6,200 103	3,600 60	7,000 117	3,700 62	2,500 42	3,000 50	1,600 27	5,000 83.3	3,150 52.5	2,300 38.3	1,500 25.0
Rated current [line]	A (rms)	5	5.3	14.1	14.1	14.1	14.1	14.1	27.2	27.7	28.3	28.3
Peak current (3.3 sec max)	A (rms)	16.6	17.2	28.2	28.2	28.2	28.2	28.2	56.6	56.6	56.6	56.6
Max cont AC A (rms) input power (3 phase 240 VAC)	6	6	15	15	15	15	15	30	30	30	30	
Rotor inertia	oz-in ² (mass) oz-in-sec ² kgm ² xlO6	5.45 0.01 99.6	9.45 0.02 172.9	13.73 0.04 251.2	35.87 0.09 656	50.79 0.13 929	56.21 0.15 1,028	111.21 0.29 2,034	50.79 0.132 929	111.21 0.288 2,034	166.21 0.431 3,040	459.48 1.190 8,404
Motor weight	lbs kg	10.0 4.5	14.0 6.4	17.0 7.7	29.0 13.2	32.0 14.5	37 16.8	51.0 23.2	32.0 15.0	57.0 26.0	65.0 29.0	112.0 51.0
Shipping weight	lbs kg	52.0 23.6	55.0 25.0	56.0 26.4	71.0 32.3	74.0 33.6	79.0 35.9	93.0 42.3	89.0 40.0	114.0 52.0	122.0 55.0	169.0 77.0

FIGURE 11-95 Technical data table for selecting servomotors. The motors are listed across the top of the table and the data are listed down the side. (Courtesy ofParker Compumotor Division.)

Problem 11-9

Select the proper motor from the table shown in Fig. 11-95. The load for the motor is 6 hp, the rated speed is 3000 rpm, and the rated torque required for the load is at least 4500 oz-in.

Solution

Since the load requires a minimum of 6 hp and requires at least 4500 oz-in. of torque, the Z-635, ZX-635, or ZFX-635 should be the smallest motor selected. The motor could be the next larger size, but it is not advisable to select too large a motor.

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