DOE Fundamentals

ELECTRICAL SCIENCE

Module 6

DC Motors

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OBJECTIVES

TERMINAL OBJECTIVE

1.0 Given the type and application of a DC motor, **DESCRIBE** the operating characteristics of that motor to include methods of speed variation, advantages of each type, and torque vs speed characteristics.

ENABLING OBJECTIVES

1.1 Using the right-hand rule for motors, **DETERMINE** the direction of the magnetic field, direction of current flow, or force on a conductor.

1.2 **STATE** the function of torque in a direct current motor and how it is developed.

1.3 **DESCRIBE** how Counterelectromotive Force (CEMF) is developed in a DC motor.

1.4 **DESCRIBE** the relationship between field current and magnetic field size in a DC motor.

1.5 **STATE** the function of the CEMF that is developed in a DC motor.

1.6 **DESCRIBE** how the speed of a DC motor is adjusted.

1.7 **DESCRIBE** the relationship between armature current and torque produced in a DC motor.

1.8 **DESCRIBE** the differences in construction between a shunt-wound and a series-wound DC motor with respect to the relationship between the field and the armature windings.

1.9 **DESCRIBE** the construction of a compounded DC motor.

1.10 **DESCRIBE** the torque-vs-speed characteristics for a shunt-wound and a series-wound DC motor.

1.11 **EXPLAIN** why starting resistors are necessary for large DC motors.

1.12 **LIST** the four nameplate ratings for a DC motor.

DC MOTOR THEORY

DC motors are widely used to drive various equipment. The speed and torque produced in a DC motor depends on a variety of factors.

EO 1.1 Using the right-hand rule for motors, **DETERMINE** the direction of the magnetic field, direction of current flow, or force on a conductor.

EO 1.2 **STATE** the function of torque in a direct current motor and how it is developed.

EO 1.3 **DESCRIBE** how Counterelectromotive Force (CEMF) is developed in a DC motor.

EO 1.4 **DESCRIBE** the relationship between field current and magnetic field size in a DC motor.

EO 1.5 **STATE** the function of the CEMF that is developed in a DC motor.

EO 1.6 **DESCRIBE** how the speed of a DC motor is adjusted.

EO 1.7 **DESCRIBE** the relationship between armature current and torque produced in a DC motor.

Inducing a Force on a Conductor

There are two conditions which are necessary to produce a force on a conductor.

- The conductor must be carrying current.
- The conductor must be within a magnetic field.

When these two conditions exist, a force will be applied to the conductor, which will attempt to move the conductor in a direction perpendicular to the magnetic field. This is the basic theory by which all DC motors operate.

Theory of Operation

Every current-carrying conductor has a magnetic field around it. The direction of this magnetic field may be found by using the left-hand rule for current-carrying conductors. When the thumb points in the direction of current flow, the fingers will point in the direction of the magnetic field produced, as shown in Figure 1.

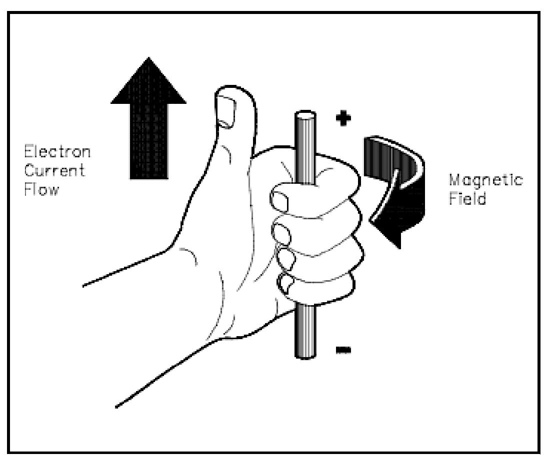

Figure 1 Left-Hand Rule for Current-Carrying Conductors

If a current-carrying conductor is placed in a magnetic field, the combined fields will be similar to those shown in Figure 2. The direction of current flow through the conductor is indicated with an "x" or a ".". The "x" indicates the current flow is away from the reader, or into the page. The "•" indicates the current flow is towards the reader, or out of the page.

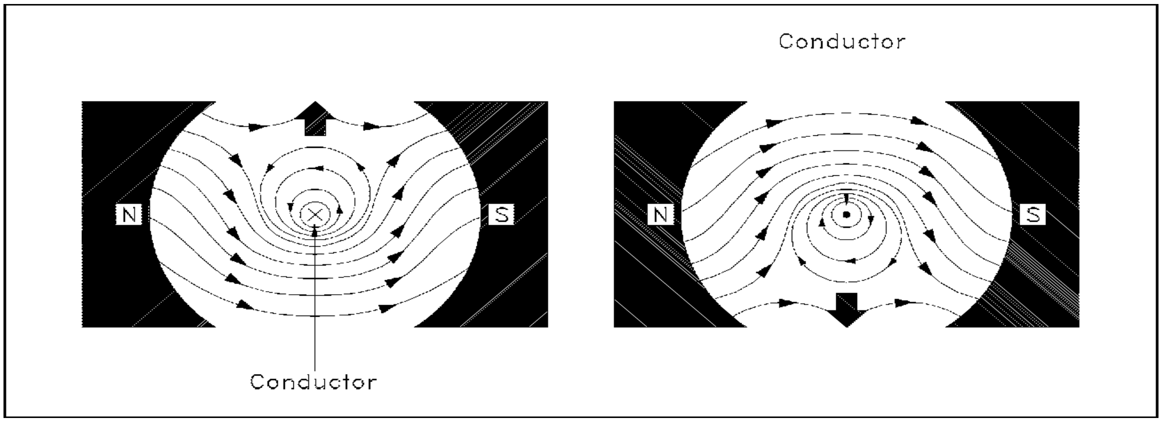

Figure 2 Current-Carrying Conductor in a Magnetic Field

Above the conductor on the left, the field caused by the conductor is in the opposite direction of the main field, and therefore, opposes the main field. Below the conductor on the left, the field caused by the conductor is in the same direction as the main field, and therefore, aids the main field. The net result is that above the conductor the main field is weakened, or flux density is decreased; below the conductor the field is strengthened, or flux density is increased. A force is developed on the conductor that moves the conductor in the direction of the weakened field (upward).

Above the conductor on the right, the field caused by the conductor is in the same direction as the main field, and therefore, aids the main field. Below the conductor on the right, the field caused by the conductor is in the opposite direction of the main field, and therefore, opposes the main field. The net result is that above the conductor the field is strengthened, or flux density is increased, and below the conductor, the field is weakened, or flux density is decreased. A force is developed on the conductor that moves the conductor in the direction of the weakened field (downward).

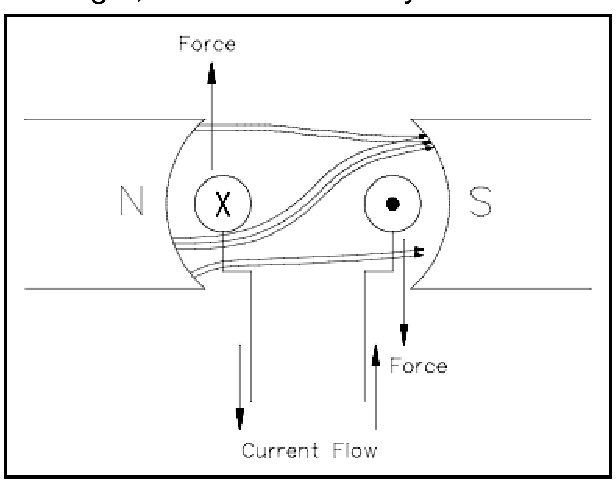

Figure 3 Motor Action

In a DC motor, the conductor will be formed in a loop such that two parts of the conductor are in the magnetic field at the same time, as shown in Figure 3.

This combines the effects of both conductors to distort the main magnetic field and produce a force on each part of the conductor. When the conductor is placed on a rotor, the force exerted on the conductors will cause the rotor to rotate clockwise, as shown on Figure 3.

You can think of these magnetic lines of force as rubber bands that are always trying to shorten themselves. The lines of force above the conductor exert a downward force due to the magnetic lines of force trying to straighten themselves.

The above explanation of how a force is developed is convenient; however, it is somewhat artificial. It is based on a fundamental principle of physics which may be stated as follows:

"A current-carrying conductor in a magnetic field tends to move at right angles to that field."

Another important way to show the relationship between the current-carrying conductor, magnetic field, and motion, is the right-hand rule for motors, as shown in Figure 4.

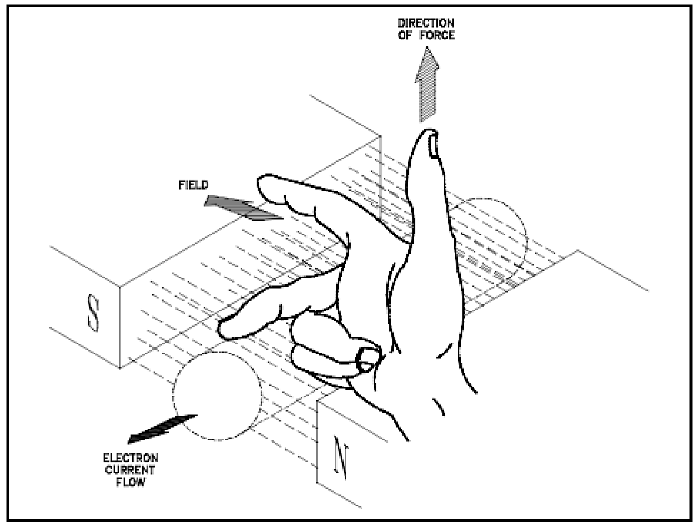

Figure 4 Right-Hand Rule for Motors

The right-hand rule for motors shows the direction in which a current-carrying conductor moves in a magnetic field. When the forefinger is pointed in the direction of the magnetic field lines, and the center finger is pointed in the direction of current flow, the thumb will point in the direction of force (motion).

Torque

Torque is defined as that force which tends to produce and maintain rotation. The function of torque in a DC motor is to provide the mechanical output or drive the piece of equipment that the DC motor is attached to.

When a voltage is applied to a motor, current will flow through the field winding, establishing a magnetic field. Current will also flow through the armature winding, from the negative brush to the positive brush as shown in Figure 5.

Since the armature is a current-carrying conductor in a magnetic field, the conductor has a force exerted on it, tending to move it at right angles to that field. Using the left-hand rule for current-carrying conductors, you will see that the magnetic field on one side is strengthened at the bottom, while it is weakened on the other side. Using the right-hand rule for motors, we can see that there is a force exerted on the armature which tends to turn the armature in the counter-clockwise direction. The sum of the forces, in pounds, multiplied by the radius of the armature, in feet, is equal to the torque developed by the motor in pound-feet (lb - ft).

It is evident from Figure 5 that if the armature current was reversed, but the field was the same, torque would be developed in the opposite direction. Likewise, if the field polarity was reversed and the armature remained the same, torque would also be developed in the opposite direction.

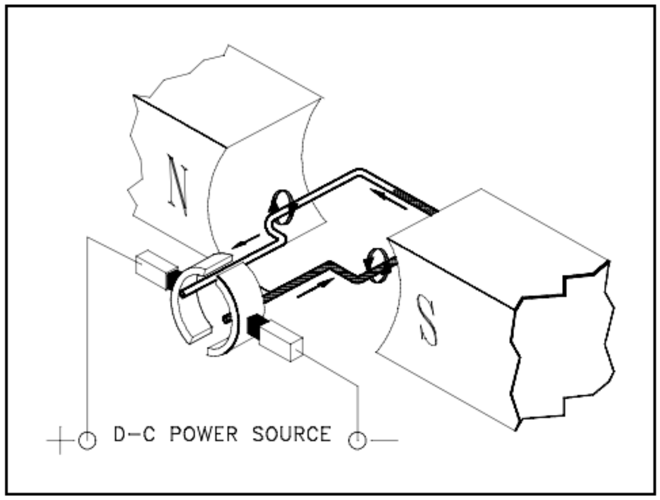

Figure 5 Armature Current in a Basic DC Motor

The force that is developed on a conductor of a motor armature is due to the combined action of the magnetic fields. The force developed is directly proportional to the strength of the main field flux and the strength of the field around the armature conductor. As we know, the field strength around each armature conductor depends on the amount of current flowing through the armature conductor. Therefore, the torque which is developed by the motor can be determined using Equation (6-1).

$$T = K \Phi I_a \tag{6-1}$$

where

T = torque, lb-ft

K = a constant depending on physical size of motor

Φ = field flux, number of lines of force per pole

I_a = armature current

Generator Action in a Motor

A generator action is developed in every motor. When a conductor cuts lines of force, an EMF is induced in that conductor.

Current to start the armature turning will flow in the direction determined by the applied DC power source. After rotation starts, the conductor cuts lines of force. By applying the left-hand rule for generators, the EMF that is induced in the armature will produce a current in the opposite direction. The induced EMF, as a result of motor operation, is called counterelectromotive force, or CEMF, as illustrated in Figure 6.

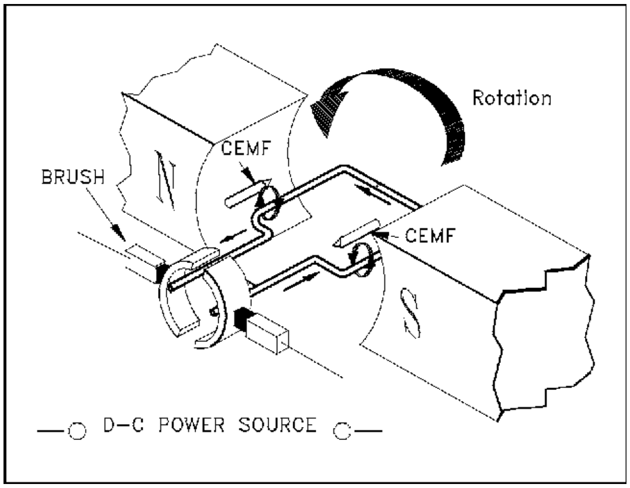

Figure 6 Counterelectromotive Force (CEMF)

Since the CEMF is generated by the action of the armature cutting lines of force, the value of CEMF will depend on field strength and armature speed, as shown in Equation (6-2).

$$E_{CEMF} = K\Phi N \qquad (6\text{-}2)$$

where

E_{CEMF} = counter EMF

K = constant

Φ = field flux strength

N = speed of the armature

The CEMF opposes the applied voltage and functions to lower armature current. The effective voltage acting in the armature of a motor is the applied voltage, minus the counter EMF. Armature current can be found by using Ohm's law, as shown in Equation (6-3).

$$I_a = \frac{E_t - E_{CEMF}}{R_a} \qquad (6\text{-}3)$$

where

I_a = armature current
E_t = terminal voltage
E_{CEMF} = counter EMF
R_a = armature resistance

DC Motor Speed

The field of a DC motor is varied using external devices, usually field resistors. For a constant applied voltage to the field (E), as the resistance of the field (R_f) is lowered, the amount of current flow through the field (I_f) increases as shown by Ohm's law in Equation (6-4).

$$\uparrow I_f = \frac{\overset{\leftrightarrow}{E}}{\downarrow R_f} \qquad (6\text{-}4)$$

An increase in field current will cause field flux (Φ_f) to increase. Conversely, if the resistance of the field is increased, field flux will decrease. If the field flux of a DC motor is decreased, the motor speed will increase. The reduction of field strength reduces the CEMF of the motor, since fewer lines of flux are being cut by the armature conductors, as shown in Equation (6-5).

$$\downarrow E_{CEMF} = \vec{K} \overset{\downarrow}{\Phi_F} \vec{N} \qquad (6\text{-}5)$$

A reduction of counter EMF allows an increase in armature current as shown in Equation (6-6).

$$\uparrow I_a = \frac{\overset{\rightarrow}{E_t} - \overset{\downarrow}{E_{CEMF}}}{\overset{\rightarrow}{R_a}} \qquad (6\text{-}6)$$

This increase in armature current causes a larger torque to be developed; the increase in armature current more than offsets the decrease in field flux as shown in Equation (6-7).

$$\uparrow T = \vec{K} \overset{\downarrow}{\Phi_F} \overset{\uparrow}{I_a} \qquad (6\text{-}7)$$

This increased torque causes the motor to increase in speed.

$$\uparrow T \propto N \uparrow$$

This increase in speed will then proportionately increase the CEMF. The speed and CEMF will continue to increase until the armature current and torque are reduced to values just large enough to supply the load at a new constant speed.

Summary

DC motor theory is summarized below.

DC Motor Theory Summary

- There are two conditions necessary to produce a force on a conductor:
  - The conductor must be carrying current.
  - The conductor must be within a magnetic field.
- The right-hand rule for motors states that when the forefinger is pointed in the direction of the magnetic field lines, and the center finger is pointed in the direction of current flow, the thumb will point in the direction of motion.
- The function of torque in a DC motor is to provide the mechanical output to drive the piece of equipment that the DC motor is attached to.
- Torque is developed in a DC motor by the armature (current-carrying conductor) being present in the motor field (magnetic field).
- CEMF is developed in a DC motor by the armature (conductor) rotating (relative motion) in the field of the motor (magnetic field).
- The function of the voltage that is developed in a DC motor (CEMF) opposes the applied voltage and results in the lowering of armature current.
- The speed of a DC motor may be changed by using resistors to vary the field current and, therefore, the field strength.

TYPES OF DC MOTORS

There are various types of DC motors found in industry today. Each type contains various characteristics that makes it desirable for certain applications.

EO 1.8 **DESCRIBE** the differences in construction between a shunt-wound and a series-wound DC motor with respect to the relationship between the field and the armature windings.

EO 1.9 **DESCRIBE** the construction of a compounded DC motor.

EO 1.10 **DESCRIBE** the torque-vs-speed characteristics for a shunt-wound and a series-wound DC motor.

DC Motor Connections

Figure 7 shows schematically the different methods of connecting the field and armature circuits in a DC motor. The circular symbol represents the armature circuit, and the squares at the side of the circle represent the brush commutator system. The direction of the arrows indicates the direction of the magnetic fields.

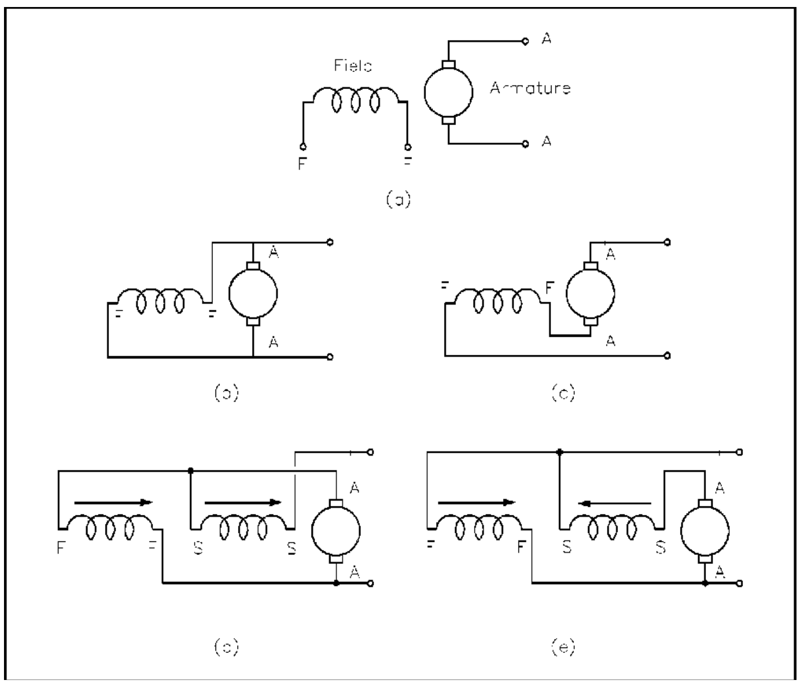

Figure 7 DC Motor Connections

- Figure 7a shows an externally-excited DC motor. This type of DC motor is constructed such that the field is not connected to the armature. This type of DC motor is not normally used.
- Figure 7b shows a shunt DC motor. The motor is called a "shunt" motor because the field is in parallel, or "shunts" the armature.

- Figure 7c shows a series DC motor. The motor field windings for a series motor are in series with the armature.
- Figures 7d and 7e show a compounded DC motor. A compounded DC motor is constructed so that it contains both a shunt and a series field. Figure 7d is called a "cumulatively-compounded" DC motor because the shunt and series fields are aiding one another. Figure 7e is called a "differentially-compounded" DC motor because the shunt and series field oppose one another.

Shunt-Wound Motor Operation

The speed-torque relationship for a typical shunt-wound motor is shown in Figure 8.

A shunt-wound DC motor has a decreasing torque when speed increases. The decreasing torque-vs-speed is caused by the armature resistance voltage drop and armature reaction. At a value of speed near 2.5 times the rated speed, armature reaction becomes excessive, causing a rapid decrease in field flux, and a rapid decline in torque until a stall condition is reached.

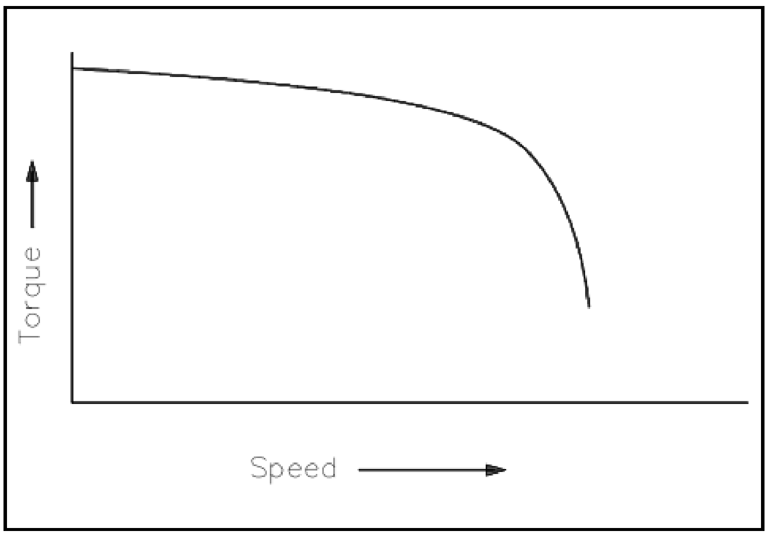

Figure 8 Torque-vs-Speed for a Shunt-Wound DC Motor

Shunt-Wound Motor Applications

The characteristics of a shunt-wound motor give it very good speed regulation, and it is classified as a constant speed motor, even though the speed does slightly decrease as load is increased. Shunt-wound motors are used in industrial and automotive applications where precise control of speed and torque are required.

Series-Wound Motor

Since the armature and field in a series-wound motor are connected in series, the armature and field currents become identical, and the torque can be expressed as shown in Equation (6-8).

$$T = KI_a^2 \tag{6-8}$$

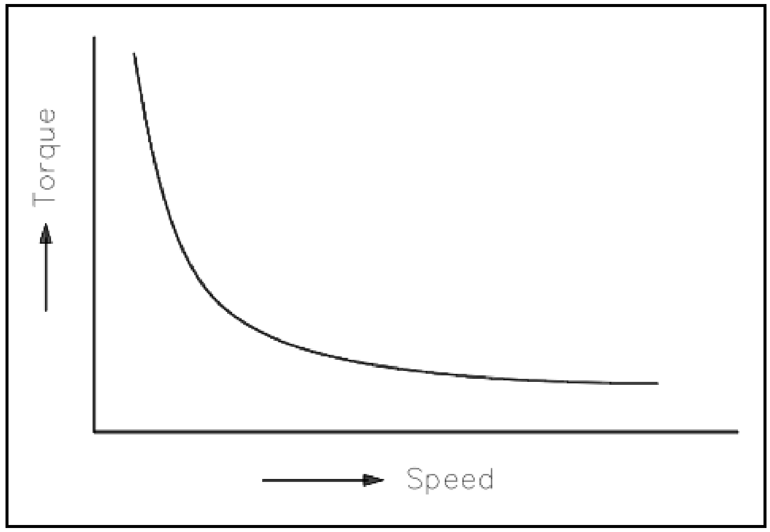

Figure 9 Torque-vs-Speed for a Series-Wound Motor

The torque-vs-speed characteristics of a series-wound motor with a constant voltage source are shown in Figure 9. As the speed decreases, the torque for a series-wound motor increases sharply. As load is removed from a series motor, the speed will increase sharply. For these reasons, series-wound motors must have a load connected to prevent damage from high speed conditions.

Series-Wound Motor Applications

The advantage of a series-wound motor is that it develops a large torque and can be operated at low speed. It is a motor that is well-suited for starting heavy loads; it is often used for industrial cranes and winches where very heavy loads must be moved slowly and lighter loads moved more rapidly.

Compounded Motor

The compounded motor is desirable for a variety of applications because it combines the characteristics of a series-wound motor and a shunt-wound motor. The compounded motor has a greater torque than a shunt motor due to the series field; however, it has a fairly constant speed due to the shunt field winding. Loads such as presses, shears, and reciprocating machines are often driven by compounded motors.

Summary

The types of DC motors are summarized below.

Types of DC Motors Summary

- In a shunt-wound motor, the field is in parallel, or "shunts" the armature.
- In a series-wound motor, the field is in series with the armature.
- A compounded DC motor is constructed so that it contains both a shunt and a series field.
- A shunt-wound DC motor has a decreasing torque as speed increases.
- The characteristics of a shunt-wound motor give it very good speed regulation, and it is classified as a constant speed motor, even though the speed does slightly decrease as load is increased.
- A series-wound motor has a rapidly increasing torque when speed decreases. As load is removed from a series-wound motor, the speed will increase sharply.
- The advantages of a series-wound motor are that it develops a large torque and can be operated at low speed. It is a motor that is well-suited for starting heavy loads.

DC MOTOR OPERATION

DC motors require special starting resistors for operation due to their unique design. Knowledge of the operation of these starting resistors is necessary to understand DC motor operation.

EO 1.11 **EXPLAIN** why starting resistors are necessary for large DC motors.

EO 1.12 **LIST** the four nameplate ratings for a DC motor.

Starting of DC Motors

At the moment a DC motor is started the armature is stationary and there is no counter EMF being generated. The only component to limit starting current is the armature resistance, which, in most DC motors is a very low value (approximately one ohm or less), as shown in Equation (6-9).

$$I_a = \frac{E_t - E_{CEMF}}{R_a} \quad (6\text{-}9)$$

In order to reduce this very high starting current, an external resistance must be placed in series with the armature during the starting period. To show why this is essential, let us consider a 10-hp motor with an armature resistance of 0.4 ohms. If the motor were supplied by a 260 VDC source, the resulting current would be as shown in Equation (6-9).

$$I_a = \frac{E_t - E_{CEMF}}{R_a}$$

$$I_a = \frac{260\,\text{VDC} - 0}{0.4\,\Omega}$$

$$I_a = 650 \text{ amps}$$

This large current is approximately twelve times greater than actual full-load current for this motor. This high current would, in all probability, cause severe damage to the brushes, commutator, or windings. Starting resistors are usually incorporated into the motor design to limit starting current to 125 to 200 percent of full load current.

The amount of starting resistance necessary to limit starting current to a more desirable value is calculated using Equation (6-10.

$$R_s = \frac{E_t}{I_s} - R_a \qquad (6\text{-}10)$$

where

R_s = starting resistance

E_t = terminal voltage

I_s = desired armature starting current

R_a = armature resistance

Example: If the full load current of the motor mentioned previously is 50 amps, and it is desired to limit starting current to 125% of this value, find the required resistance that must be added in series with the armature.

$$R_s = \frac{E_t}{I_s} - R_a$$

$$R_s = \frac{260\,\text{VDC}}{125\%(50\ \text{amps})} - 0.4\,\Omega$$

$$R_s = 3.76\,\Omega$$

The starting resistors are used in a DC motor by placing them in the starting circuit of the motor controller that is used to start the DC motor. Starting resistors are normally of variable resistances, with the value of resistance in the circuit at any time being either manually or automatically controlled. The maximum amount of resistance will always be inserted when the motor is first started. As the speed of the motor increases, counter EMF will begin to increase, decreasing armature current. The starting resistors may then be cut out, in successive steps, until the motor reaches full running speed.

DC Motor Ratings

The nameplate ratings of a DC motor refer to the conditions of voltage, current, speed, and power at which the motor is normally operated. The principal rating is known as the *continuous* rating, which is the rating described on the nameplate of a motor. The continuous power rating is a thermal rating. At this power, the motor can be operated for long periods of time without a large rise in temperature and beyond the limits of the conductor insulating material, bearings and other components, which are greatly affected by temperature.

Summary

DC motor operation is summarized below.

DC Motor Operation Summary

- Starting resistors are necessary for large DC motors to prevent damage due to high currents while starting the motor.
- Starting resistors are placed in the starting circuits for the controllers that start the motor. When the motor reaches full speed, the starting resistors are cut out of the circuit.
- The four nameplate ratings for a DC motor include:
  - voltage
  - current
  - speed
  - power