CHAPTER 7

Direct Current Motors

OBJECTIVES

After studying this chapter, you should be able to:

- Explain the theory of operation of electric motors in general and DC motors in particular.
- Distinguish the characteristics of series-wound, shunt-wound, compound, and permanent-magnet motors.
- Use the torque-speed curve of a motor to predict its performance.
- Select a DC motor based on mechanical requirements.
- Understand the operation of linear amplifier drivers for DC motors that incorporate power transistors, IC amplifiers, Darlington transistors, and power MOSFETS.
- Understand DC motor-speed control using pulse-width-modulation concepts.
- Understand operating a DC motor from rectified AC, using silicon-controlled-rectifier circuits.
- Understand the operating principles of brushless DC motors.

INTRODUCTION

An indispensable component of the control system is the actuator. The actuator is the first system component to actually move, converting electrical energy into mechanical motion. The most common type of actuator is the electric motor.

Motors are classified as either DC or AC, depending on the type of power they use. AC motors (covered in Chapter 9) have some advantages over DC motors: They tend to be smaller, more reliable, and less expensive. However, they generally run at a fixed speed that is determined by the line frequency. DC motors have speed-control capability, which means that speed, torque, and even direction of rotation can be changed at any time to meet new conditions. Also, smaller DC motors commonly operate at lower voltages (for example, a 12-V disk drive motor), which makes them easier to interface with control electronics.

7.1 THEORY OF OPERATION

The discovery that led to the invention of the electric motor was simply this: A current-carrying conductor will experience a force when placed in a magnetic field. The conductor can be any metal—iron, copper, aluminum, and so on. The direction of the force is perpendicular to both the magnetic field and the current (Figure 7.1). A demonstration of this principle is easy to perform with a strong magnet, flashlight battery, and a wire and is highly recommended! Place the wire between the magnet poles and alternately connect and disconnect the wire from the battery. Each time you complete the circuit, you should feel a little tug on the wire. The magnitude of the force on the wire can be calculated from the following equation:

$$F = IBL \sin \theta \tag{7.1}$$

where
F = force on the conductor (in Newtons)
I = current through the conductor (in amperes)
B = magnetic flux density (in gauss)
L = length of the wire (in meters)
θ = angle between the magnetic field and current

An electric motor must harness this force in such a way as to cause a rotary motion. This can be done by forming the wire in a loop and placing it in the magnetic field (Figure 7.2). The loop (or *coil*) of wire is allowed to rotate about the axis shown and is

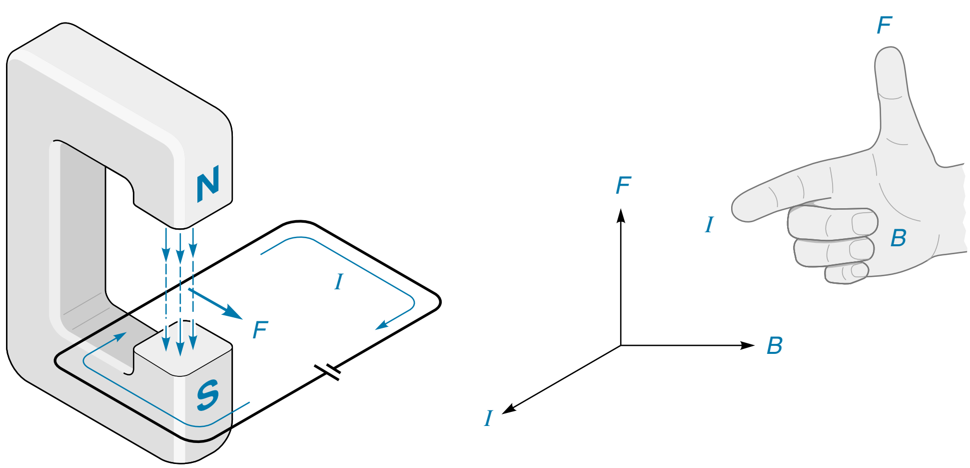
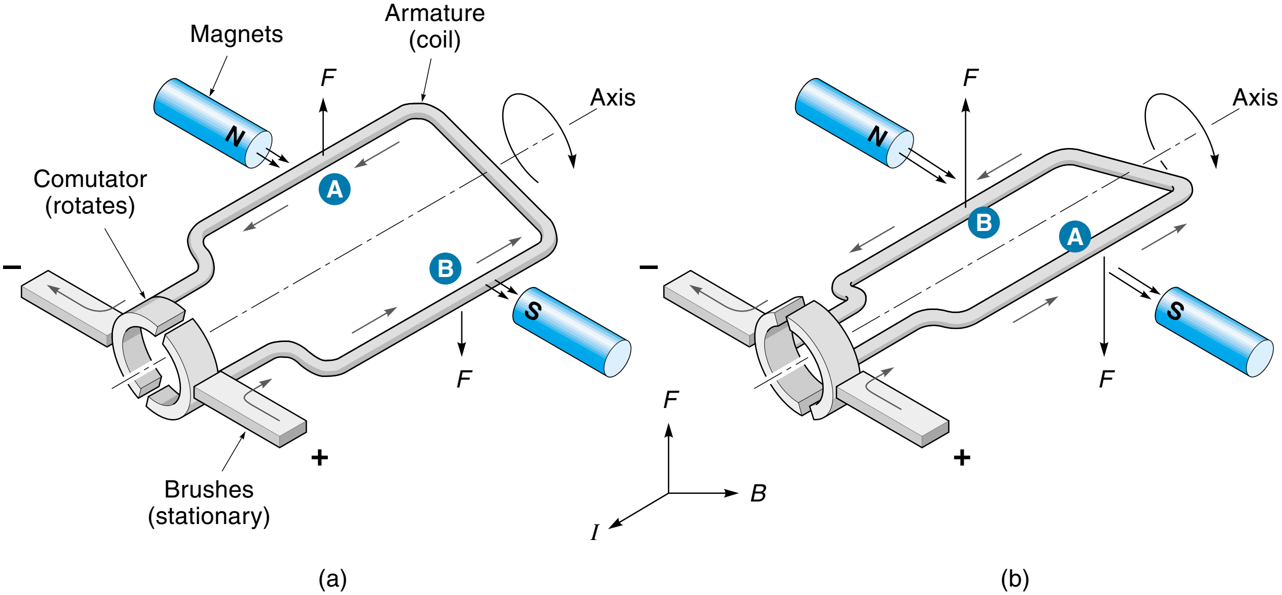


Figure 7.1 Action of force on a wire in a magnetic field.

(a) Experimental setup

(b) Directions of I, F, and B are mutually orthogonal (conventional current flow)

Figure 7.2
A simple DC motor action (conventional flow).



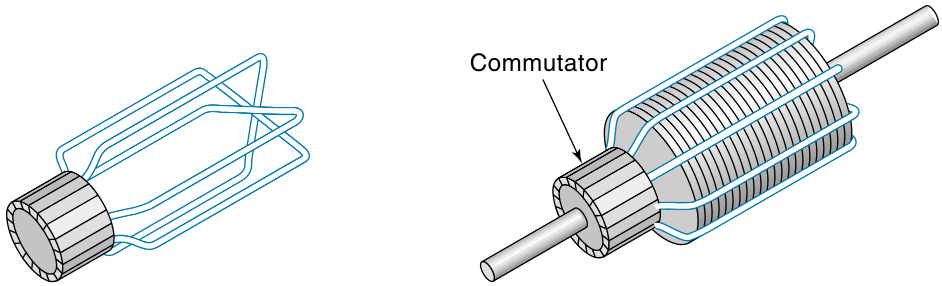
called the **armature** winding. The armature is placed in a magnetic field called the **field.** The **commutator** and **brushes** supply current to the armature while allowing it to rotate.

To understand how the motor works, look at Figure 7.2(a). Notice that wire segments A and B of the coil are in the same magnetic field, but the current in wire segment A is coming out of the page, whereas the current in wire segment B is going in. Applying the force diagram from Figure 7.1(b) (and repeated in Figure 7.2), we see that wire segment A of the coil would be forced up, whereas wire segment B would be forced down. These forces would cause the coil to rotate clockwise. Figure 7.2(b) shows the situation after the coil has rotated about 90°. The current has now reversed direction in the coil because the commutator contacts have rotated and are now making contact with the opposite brush. Now wire segment A of the coil will be forced down and wire segment B up, which causes the armature to continue rotating clockwise. **Torque,** as explained in Chapter 5, is the rotational force a motor can exert. Notice that the torque will be at a maximum when the coil is horizontal and will drop to zero when the coil is vertical (similar to peddling a bicycle).

To reverse the direction of the motor, polarity of the voltage to the commutator is reversed. This causes the forces on the armature coil to be reversed, and the motor would then run in the opposite direction.

Figure 7.3 shows the armature of a practical motor. Notice that there are multiple coils and each coil experiences the forces described in the preceding paragraph and so contributes to the overall torque of the motor. Each coil is connected to a separate pair

Figure 7.3
DC motor armature.



of commutator segments, causing the current in each coil to switch directions at the proper time for that individual coil. The overall effect is to provide approximately the same torque for any armature position (like a multipiston engine).

One of the most important operating parameters of any motor is torque. Electric motor torque is directly proportional to the force on the armature wires. From Equation 7.1, we see that the force is proportional to the magnetic field and current (not voltage). By gathering the mechanical parameters of the motor (such as number of poles) into a single constant *K,* the motor torque can be expressed as

$$T = K_T I_A \phi \tag{7.2}$$

where
T = motor torque
K_T = a constant based on the motor construction
I_A = armature current
ϕ = magnetic flux

So far we have been looking at how the motor converts electrical energy to mechanical energy. It turns out that the very same device (motor) is also capable of converting mechanical energy to electrical energy, in which case it is called a generator. For example, if the armature coil of Figure 7.2 were rotated in the magnetic field by some external force, a voltage [called the *electromotive force* (EMF)] would appear on the commutator segments. The magnitude of the EMF is given in Equation 7.3:

$$\text{EMF} = K_E \phi S \tag{7.3}$$

where
EMF = voltage generated by the turning motor
K_E = a constant based on motor construction
ϕ = magnetic flux
S = speed of motor (rpm)

Although it may seem strange, this EMF voltage is being generated even when the motor is running on its own power, but it has the opposite polarity of the line voltage; hence, it is called the **counter-EMF** (CEMF). *Its effect is to cancel out some of the line voltage*. In other words, the actual voltage available to the armature is the line voltage minus the CEMF:

$$V_A = V_{\mathrm{ln}} - \mathrm{CEMF} \tag{7.4}$$

where

V_A = actual voltage available to the armature
V_{ln} = line voltage supplied to the motor
CEMF = voltage generated within the motor

You can not directly measure V_A with a voltmeter because it is an effective voltage inside the armature. However, there *is* physical evidence that the CEMF exists because the armature current is also reduced, as indicated in Equation 7.5:

$$I_A = \frac{V_{\mathrm{ln}} - \mathrm{CEMF}}{R_A} \tag{7.5}$$

where

I_A = armature current
V_{ln} = line voltage to the motor
R_A = armature resistance
CEMF = voltage generated within the motor

Equation 7.5 (which is in the form of Ohm's law) tells us that the armature current is a function of the applied voltage minus the CEMF. Because CEMF increases with motor speed, the faster the motor runs, the less current the motor will draw, and consequently its torque will diminish. This explains why most DC motors have a finite maximum speed; eventually, if the motor keeps going faster, the CEMF will nearly cancel out the line voltage, and the armature current will approach zero.

The actual relationship between motor speed and CEMF follows and is derived from Equation 7.3:

$$S = \frac{\mathrm{CEMF}}{K_E \phi} \tag{7.6}$$

where

S = speed of the motor (rpm)
CEMF = voltage generated within the motor
K_E = a motor constant
ϕ = magnetic flux

Looking at Equation 7.6, we see that the motor speed is directly proportional to the CEMF (voltage) and (surprisingly) inversely proportional to the field flux.

EXAMPLE 7.1

A 12 Vdc motor has an armature resistance of 10 Ω and according to its spec sheet generates a CEMF at the rate of 0.3 V/100 rpm. Find the actual armature current at 0 rpm and at 1000 rpm.

SOLUTION

We can find the armature current with Equation 7.5. For the first case, when the motor isn't turning at all (0 rpm), the CEMF will be 0 V:

$$I_A = \frac{V_{\text{ln}} - \text{CEMF}}{R} = \frac{12\text{ V} - 0\text{ V}}{10} = 1.2\text{ A}$$

For the second case (1000 rpm), determine the CEMF before applying Equation 7.5. Given the CEMF rate of 0.3 V/100 rpm,

$$\text{CEMF} = \frac{0.3\text{ V}}{100\text{ rpm}} \times 1000\text{ rpm} = 3\text{ V}$$

Then

$$I_A = \frac{V_{\text{ln}} - \text{CEMF}}{R_a} = \frac{12\text{ V} - 3\text{ V}}{10} = \frac{9\text{ V}}{10} = 0.9\text{ A}$$

Thus, we see that the armature current is reduced in the running motor.

DC motors have a property called speed regulation. **Speed regulation** is the ability of a motor to maintain its speed when the load is applied. The basis of this self-regulation is the CEMF. When the motor's load is increased, the speed tends to decrease, but the lower speed reduces the CEMF, which allows more current into the armature. The increased current results in increased torque, which prevents the motor from slowing further. Speed regulation is usually expressed as a percentage, as shown in Equation 7.7:

$$\%\text{ speed regulation} = \frac{S_{\text{NL}} - S_{\text{FL}}}{S_{\text{FL}}} \times 100 \tag{7.7}$$

where

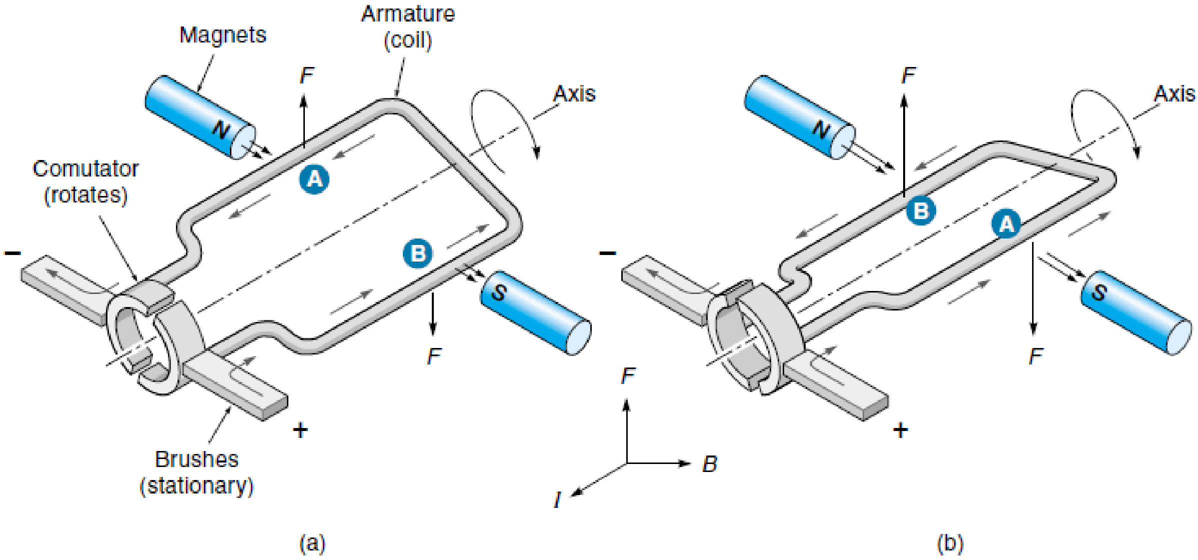
S_{NL} = no-load speeds
S_{FL} = full-load speeds

Tugas 2

Topik : Motor DC

1) Jelaskan singkat masing-masing kelebihan dan kekurangan dari motor AC dan motor DC.

2) Jelaskan cara kerja motor DC berdasarkan gambar berikut.



3) Apa yang dimaksud dengan CEMF? Jelaskan bagaimana CEMF dapat sangat mempengaruhi performa kerja motor DC.

4) Jelaskan satu cara untuk membuktikan bahwa motor DC menghasilkan CEMF.

5) Sebuah motor menghasilkan CEMF sebesar 0.4 V/100 rpm dan memiliki tahanan *armature* 20 Ω. Motor tersebut diberi tegangan sebesar 10 volt. Tentukan :

   a. Berapa besar arus yang melewati *armature* pada saat motor baru mulai bergerak (0 rpm)?
   b. Berapa besar arus yang melewati *armature* pada saat motor telah mencapai kecepatan putar 1500 rpm?

Jawaban dikirimkan ke e-mail:

randyesaputra@yahoo.com

paling lambat Jumat, 20 Februari 2015 jam 17.00