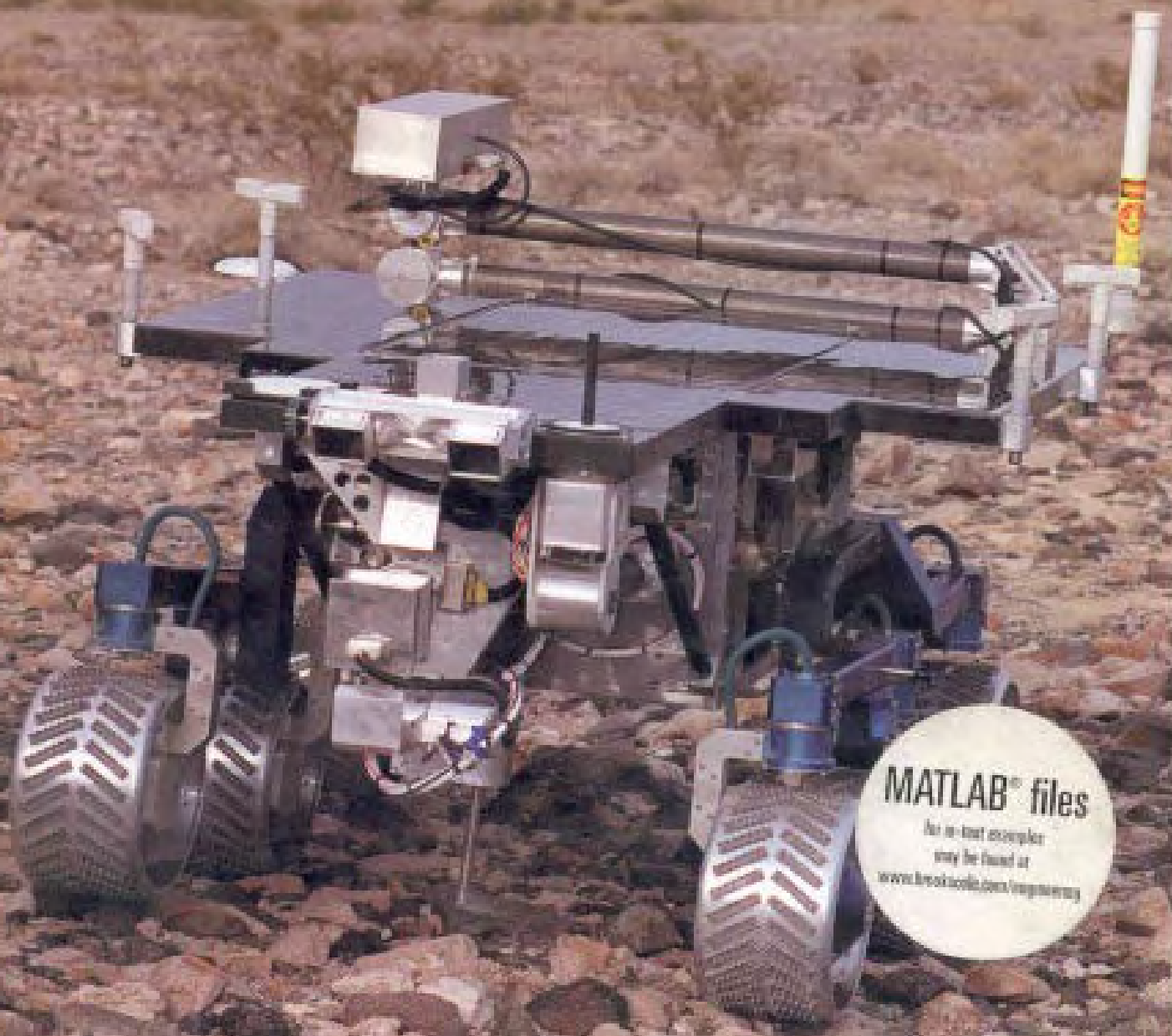


FUNDAMENTALS OF ELECTRIC DRIVES

MOHAMED A. EL-SHARKAWI



Fundamentals of Electric Drives

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- b. Use Equation (3.56) to compute the average voltage across the load.

$$V_{\text{ave}} = KV_s = 0.3 (80) = 24 \text{ V}$$

- c. The average voltage across the diode $V_{d \text{ ave}}$ is the complement of the average voltage across the load.

$$V_{d \text{ ave}} = \frac{1}{\tau} \int_{t_{\text{on}}}^{\tau} V_s dt = (1 - K)V_s = 0.7 (80) = 56 \text{ V}$$

$V_{d \text{ ave}}$ can also be computed by subtracting V_{ave} from the source voltage V_s .

- d. The average load current is

$$I_{\text{ave}} = \frac{V_{\text{ave}}}{R} = \frac{24}{4} = 6 \text{ A}$$

- e. Since we assume that the current is ripple-free (no harmonics), and the load voltage is also ripple-free, the load power can be computed as

$$P = V_{\text{ave}} I_{\text{ave}} = 144 \text{ W}$$

3.9 dc/ac CONVERSION

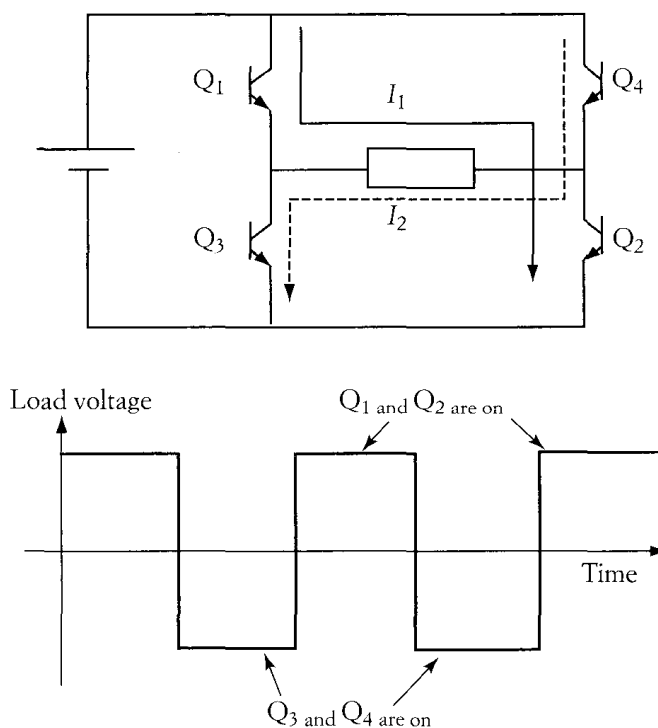
This type of converter is also known as an inverter. Here, the input is a dc waveform and the output is an ac waveform. The inverter is widely used in uninterruptible power supplies, variable speed ac motors, and dc transmission lines.

Keep in mind that the term ac does not mean a perfect sinusoidal waveform; rather, it refers to a waveform that has positive and negative portions in each cycle. Furthermore, the ac waveform may have a small dc component; that is, the average value is not necessarily zero.

3.9.1 SINGLE-PHASE, dc/ac CONVERTER

Figure 3.28 shows a simple dc/ac inverter known as *H-bridge*. It consists of a dc source, four transistors, and a load. For simplicity, we shall assume that the load is resistive. At any period, only two transistors in opposite legs are turned on. To prevent short-circuiting the supply, any two transistors on the same leg cannot be turned on at the same time (either Q_1 and Q_2 , or Q_3 and Q_4 , are turned on simultaneously). Figure 3.28 also shows the voltage across the load. When Q_1 and Q_2 are closed, the current I_1 flows to the load. When Q_3 and Q_4 are closed, the current I_2 flows in the reverse direction to I_1 . The load current in this case is alternating between positive and negative values. If the switching periods of all transistors are

FIGURE 3.28

dc/ac H-bridge and its ideal waveform

equal, the average component of the current is zero, and the waveform of the current or voltage is symmetrical around the time axis.

Notice that the waveform of Figure 3.28 is not sinusoidal. Nevertheless, it is an ac waveform. Reducing or prolonging the closing time of all transistors adjusts the frequency of the load voltage. The smaller the on time is, the higher is the frequency.

3.9.2 THREE-PHASE dc/ac CONVERTER

Three-phase waveforms can be obtained by using a relatively more elaborate dc/ac inverter similar to the one shown in Figure 3.29. The inverter is composed of six switches and six diodes. The diodes are used to allow the energy to flow back to the source. This is a requirement in most electric drive systems where the motor delivers energy back to the source under certain drive conditions. As discussed at the end of Chapter 2, when inductive load is interrupted, a large voltage builds up across the switch terminals to allow the energy stored in the inductive elements to return back to the source. The diodes in the figure provide a safe path for the flow of this energy back to the source, thus protecting the transistors from being damaged. The midpoint of each leg of the inverter is connected to the correspondingly-labeled load terminal. The load is shown separately on the right side of the figure.

Direct substitution in Equation (6.19) yields

$$\frac{\sqrt{2} \times 120}{2\pi} [\cos(60) - \cos(60 + 150)] = \frac{150}{360} \times 2.5 \times \omega + 5 \times 4$$

$$\omega = 16.22 \text{ rad/sec}$$

$$n = 154.88 \text{ rpm}$$

The developed power is

$$P_d = E_a I_{\text{ave}} = K\phi\omega I_{\text{ave}} = 2.5 \times 16.22 \times 4 = 162 \text{ W}$$

which is about 21% of the motor rating.

6.1.4.2 SINGLE-PHASE, FULL-WAVE DRIVES

A full-wave drive can be realized by using one of the two circuits shown in Figures 6.10 and 6.11. The circuit in Figure 6.10 consists of four SCRs connected in a full-wave bridge. The switching of the SCRs is dependent on the polarity of the source voltage v_s . The current i_1 (solid lines) flows when the ac waveform of the source voltage is in the positive half-cycle, and SCRs S_1 and S_2 are triggered. Similarly, current i_2 (dashed lines) flows when the waveform of the source voltage is in the negative half, and S_3 and S_4 are triggered. In either half of the cycle, the current will flow in the same direction inside the motor.

FIGURE 6.10

Full-wave drive using four-SCR bridge

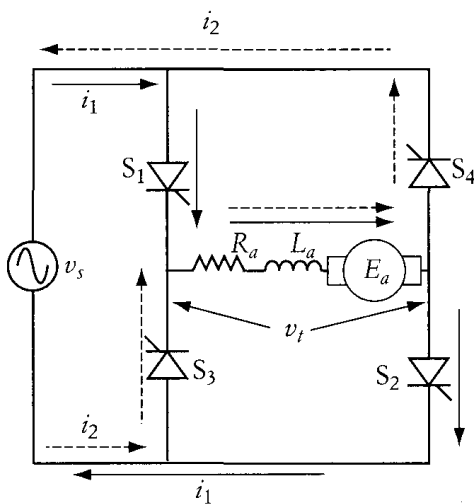


FIGURE 6.11

Full-wave drive using two SCRs and a center-tap transformer

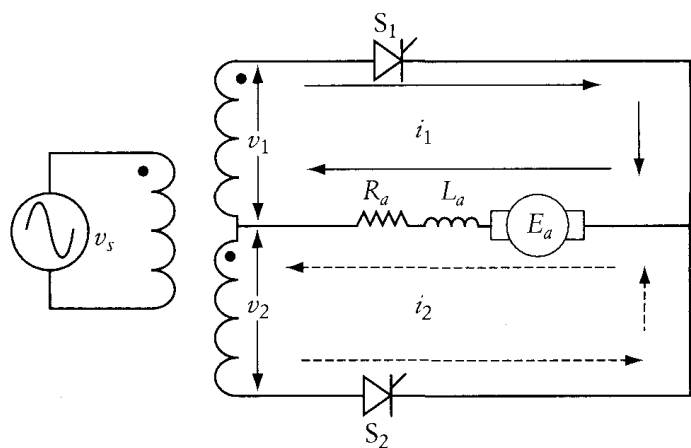
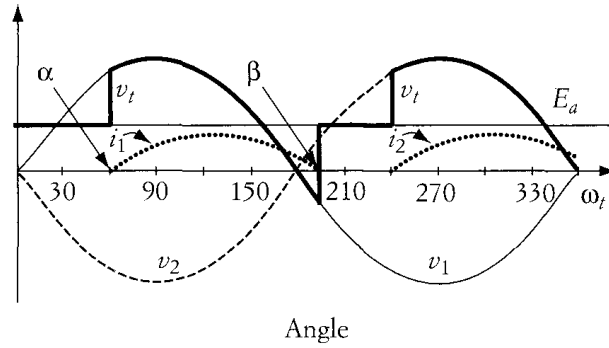


FIGURE 6.12

Waveforms of circuit in Figure 6.11

The circuit in Figure 6.11 shows another alternative where two SCRs and a center-tap transformer are used. The secondary of the transformer should have double the voltage rating of the motor; that is,

$$V_1 = V_2 = \text{rated armature voltage}$$

When the source voltage v_s is in the positive half of its cycle and S_1 is triggered, i_1 flows in the upper half of the transformer's secondary windings. When the source voltage is in the negative part and S_2 is closed, i_2 flows in the lower half of the secondary windings. Again, in either half of the source waveform, the armature current of the machine is unidirectional.

The waveforms of the circuit in Figure 6.11 are shown in Figure 6.12. The figure shows v_1 and v_2 in reference to the center point of the transformer. When v_1 is in the positive part of its cycle and S_1 is triggered at α , the terminal voltage of the motor v_t is equal to v_1 and the motor current is i_1 . Because i_1 flows beyond 180° , the terminal voltage of the motor v_t becomes negative. When i_1 reaches zero at β , v_t is equal to E_a until S_2 is triggered. Similarly, during the positive half of v_2 , i_2 flows and the terminal voltage of the motor equals v_2 .

The average terminal voltage of the motor is calculated by

$$V_{t \text{ ave}} = E_a + I_{\text{ave}} R_a$$

or

$$\frac{2}{2\pi} \int_0^\pi v_t d\omega t = E_a + \frac{2R_a}{2\pi} \int_0^\pi i d\omega t$$

$$\frac{1}{\pi} \left[\int_\alpha^\beta v_t d\omega t + \int_\beta^{\alpha+\pi} v_t d\omega t \right] = E_a + \frac{R_a}{\pi} \int_\alpha^\beta i d\omega t$$

Using the same procedure explained in Equations (6.16) to (6.18), the equation of the armature circuit is

FIGURE 9.24

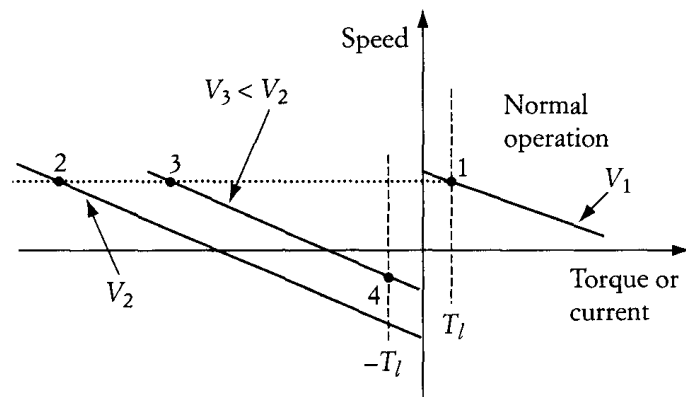
Effect of voltage reduction during TVR braking

FIGURE 9.25

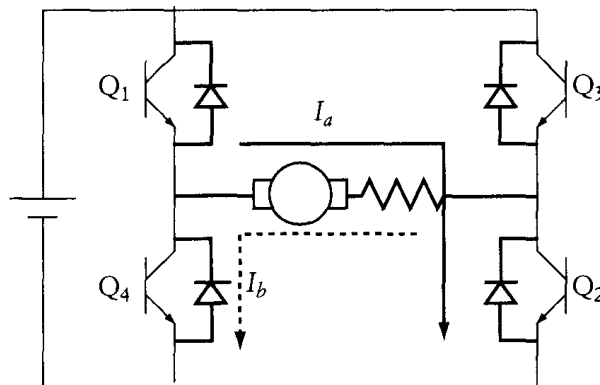
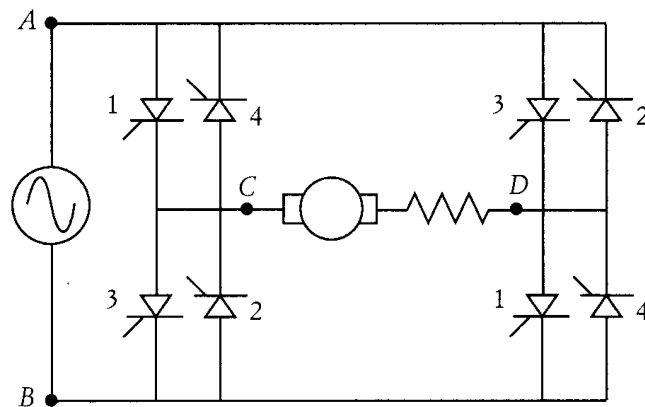
TVR braking circuit with dc source

Figure 9.25 shows one schematic that can be used to achieve this type of braking. When transistors Q_1 and Q_2 are triggered, the terminal voltage of the motor has the positive polarity at the emitter side of Q_1 . If Q_3 and Q_4 are triggered, and Q_1 and Q_2 are turned off, the voltage across the motor has its polarities reversed. The diodes in the figure are for freewheeling. To reduce the braking current due to the TVR, transistors Q_3 and Q_4 must be pulse-width modulated to reduce the voltage across the motor terminals.

For an ac source, a TVR braking circuit can be constructed from solid-state switches such as SCRs. Such a circuit is shown in Figure 9.26. The SCRs labeled 1 and 2 are used in normal operation. SCRs 1 are triggered when terminal A is positive with respect to B . SCRs 2 are triggered when terminal B is positive with respect to A . This makes terminal C of the motor positive regardless of the polarity of the source volt-

FIGURE 9.26

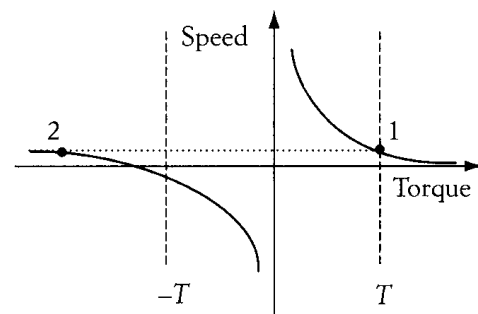
TVR braking circuit with ac source

age. There is no need here for freewheeling diodes because the SCRs are naturally commutated, and the circuit is a full-wave bridge.

To do the TVR braking, SCRs 3 are turned on when terminal *A* is positive with respect to *B*. Also, SCRs 4 are triggered when *B* is positive with respect to *A*. This switching sequence reverses the polarities of the motor (*D* is positive with respect to *C*). Keep in mind that the triggering angle of SCRs 3 and 4 must be adjusted to reduce the voltage across the motor during the TVR braking.

The motor characteristics for the TVR braking circuit of Figure 9.26 are shown in Figure 9.27. Here we are assuming that the load torque is bidirectional. The original motor operating point is point 1. After SCRs 1 and 2 are commutated and SCRs 3 and 4 are triggered, the motor moves to point 2. The motor characteristic is mainly in the third quadrant, but because of the reduction in the terminal voltage, the characteristics tend to extend to the second quadrant. The motor settles at an operating point where the load and motor characteristics meet.

FIGURE 9.27

TVR braking characteristics using the circuit in Figure 9.26**EXAMPLE 9.6**

Consider the circuit in Figure 9.26. Assume that the dc, separately excited motor has an armature resistance of $1\ \Omega$ and a field constant $K\phi = 3\ \text{V sec}$. The ac voltage source of the circuit is 480 V. Assume that the load torque is bidirectional and equal to 120 Nm in either direction of rotation. The triggering angle of SCRs 1 and 2 is 30° and the current is continuous. A TVR braking is used. Calculate the triggering