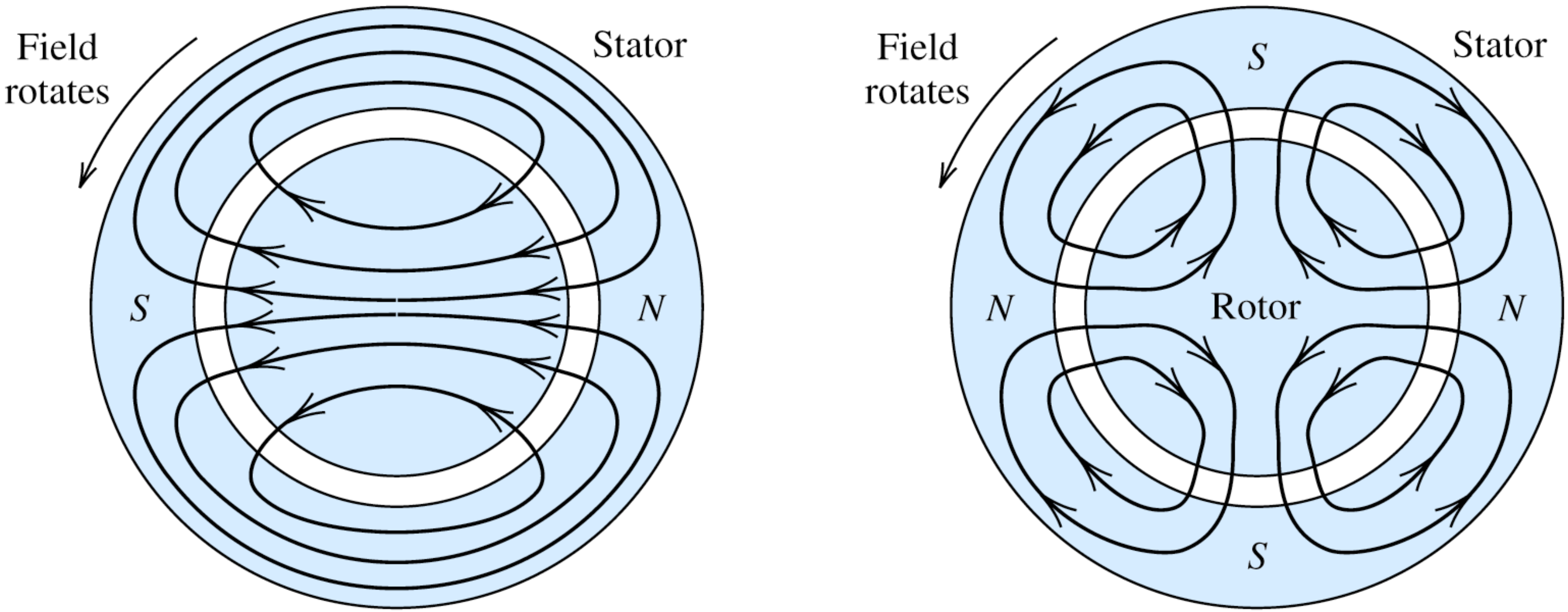
AC MACHINES

AC Machines

1. Select the proper ac motor type for various applications.
2. State how torque varies with speed for various ac motors.
3. Compute electrical and mechanical quantities for ac motors.
4. Use motor nameplate data.
5. Understand the operation and characteristics of three-phase induction motors, three-phase synchronous machines, various types of single- phase ac motors, stepper motors, and brushless dc motors.



(a) Two-pole machine

(b) Four-pole machine

Figure 17.1 The field established by the stator windings of a three-phase induction machine consists of an even number of magnetic poles. The field rotates at a speed known as synchronous speed.

Rotating Stator Field

We see that the stator windings of three-phase induction machines set up magnetic poles that rotate around the circumference of the stator.

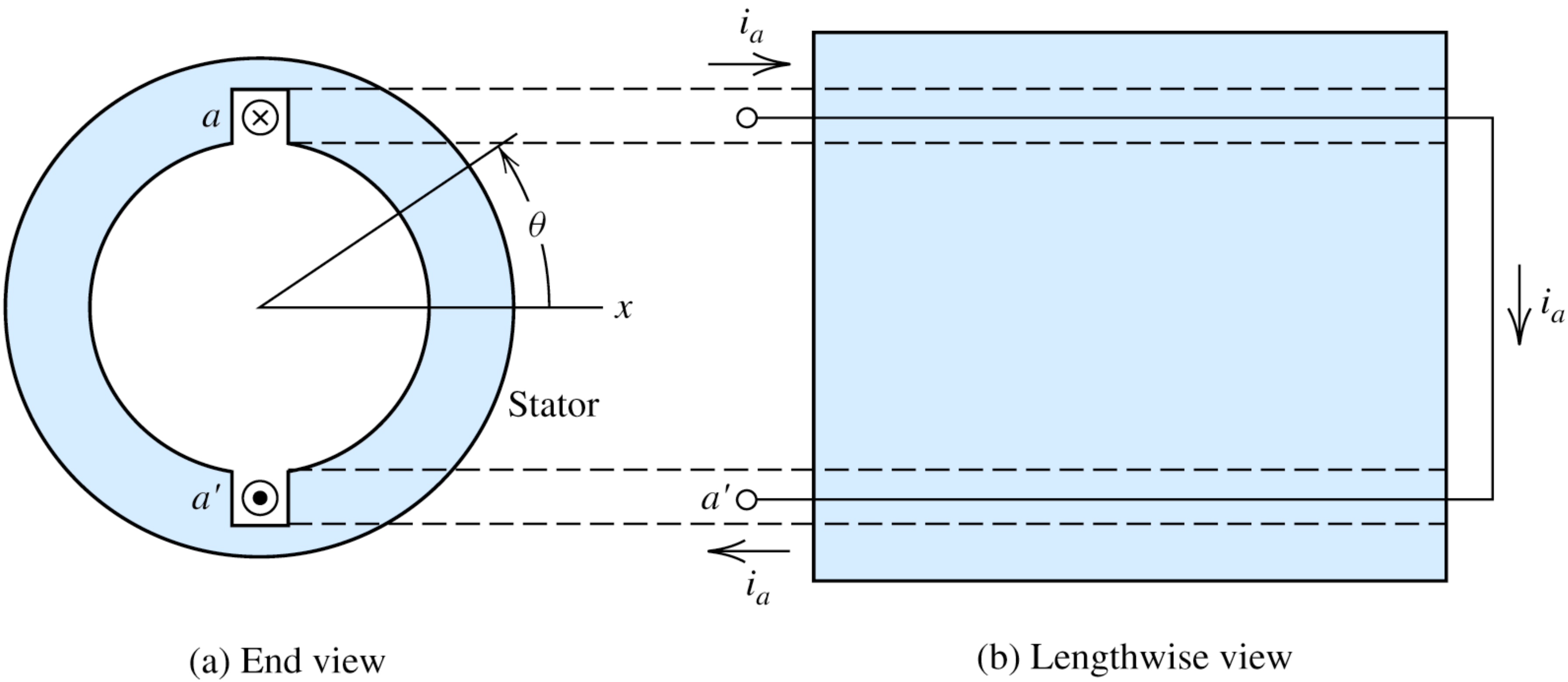


Figure 17.2 Two views of a two-pole stator showing one of the three windings. For simplicity, we represent the winding with a single turn, but in a real machine each winding has many turns distributed around the circumference of the stator such that the air-gap flux varies sinusoidally with θ.

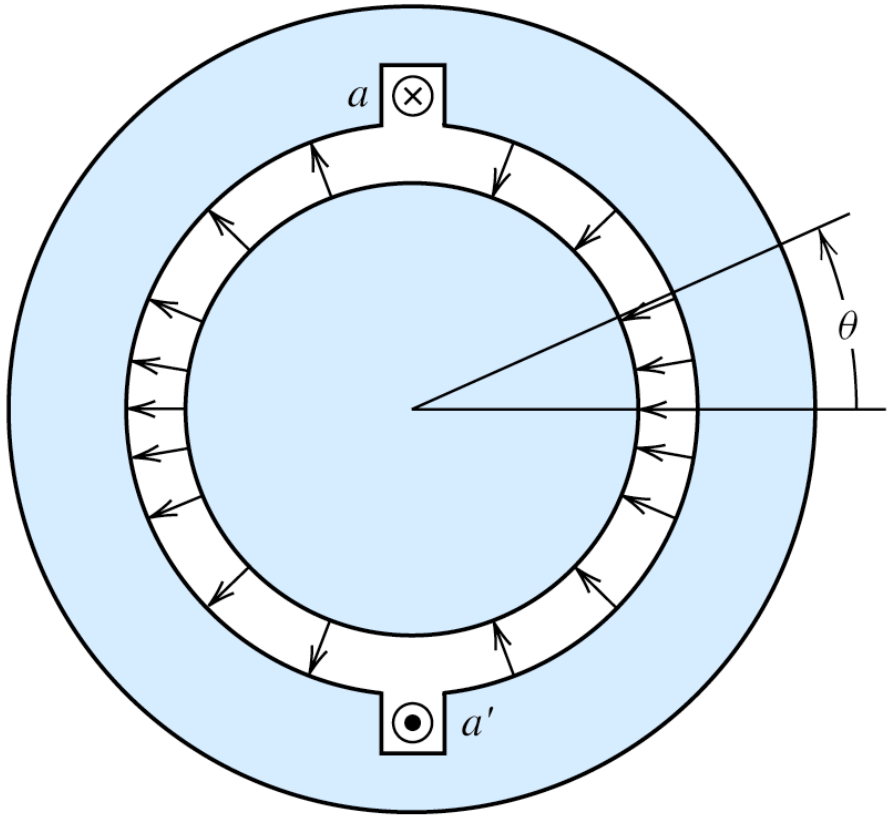


Figure 17.3 The field produced by the current in winding a varies sinusoidally in space around the circumference of the gap. The field is shown here for the positive maximum of the current $i_a(t)$. As illustrated, the field is strongest in magnitude at $\theta = 0$ and at $\theta = 180^\circ$. Furthermore, the current and the field vary sinusoidally with time. Over time, the field dies to zero and then builds up in the opposite direction.

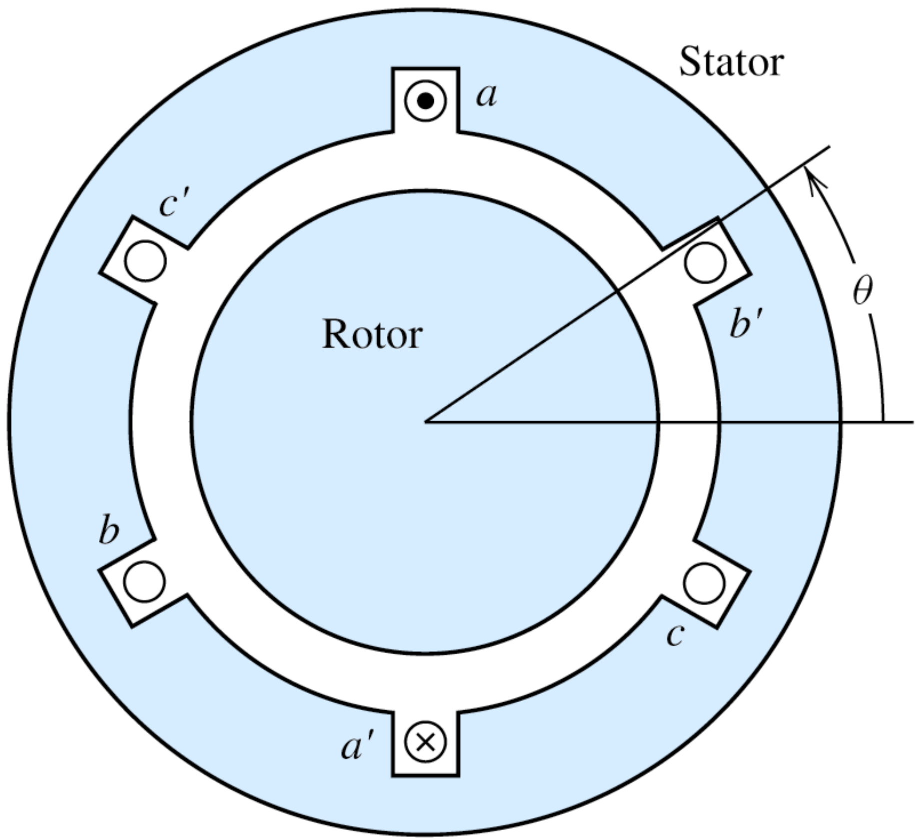
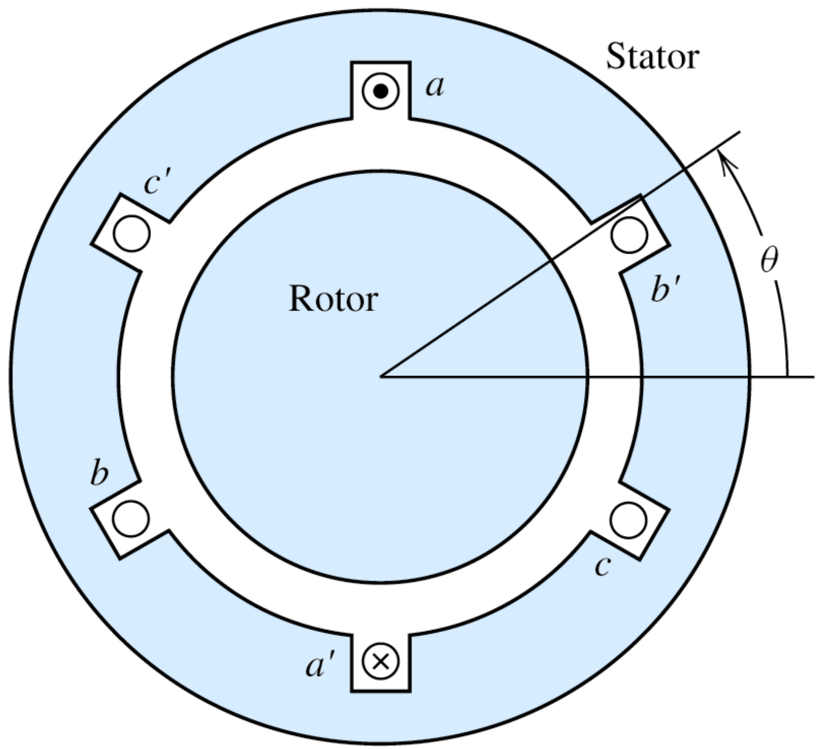


Figure 17.4 The stator of a two-pole machine contains three identical windings spaced 120° apart.

$$B_a = K i_a(t)\cos(\theta)$$
$$B_b = K i_b(t)\cos(\theta - 120^\circ)$$
$$B_c = K i_c(t)\cos(\theta - 240^\circ)$$



$$B_{\text{gap}} = K i_a(t)\cos(\theta) + K i_b(t)\cos(\theta - 120^\circ) + K i_c(t)\cos(\theta - 240^\circ)$$

$$i_a(t) = I_m \cos(\omega t)$$

$$i_b(t) = I_m \cos(\omega t - 120^\circ)$$

$$i_c(t) = I_m \cos(\omega t - 240^\circ)$$

$$B_{\text{gap}} = KI_m \cos(\omega t)\cos(\theta) + KI_m \cos(\omega t - 120^\circ)\cos(\theta - 120^\circ)$$
$$+ KI_m \cos(\omega t - 240^\circ)\cos(\theta - 240^\circ)$$

$$\cos(x)\cos(y) = (1/2)[\cos(x - y) + \cos(x + y)]$$

$$B_{\text{gap}} = \frac{3}{2} KI_m \cos(\omega t - \theta) + \frac{1}{2} KI_m [\cos(\omega t + \theta)$$
$$+ \cos(\omega t + \theta - 240^\circ) + \cos(\omega t + \theta - 480^\circ)]$$

$$\left[\cos(\omega t+\theta)+\cos\left(\omega t+\theta-240^\circ\right)+\cos\left(\omega t+\theta-480^\circ\right)\right]=0$$

$$B_{\text{gap}}=B_m\cos\left(\omega t-\theta\right)$$

Thus, the field in the gap rotates counterclockwise with an angular speed ω.

Synchronous Speed

$$\omega_s = \frac{\omega}{P/2}$$

$$n_s = \frac{120f}{P}$$

Table 17.1. Synchronous Speed versus Number of Poles for $f = 60$ Hz

P	n_s
2	3600
4	1800
6	1200
8	900
10	720
12	600

The direction of rotation of a three-phase induction motor can be reversed by interchanging any two of the three line connections to the three-phase source.

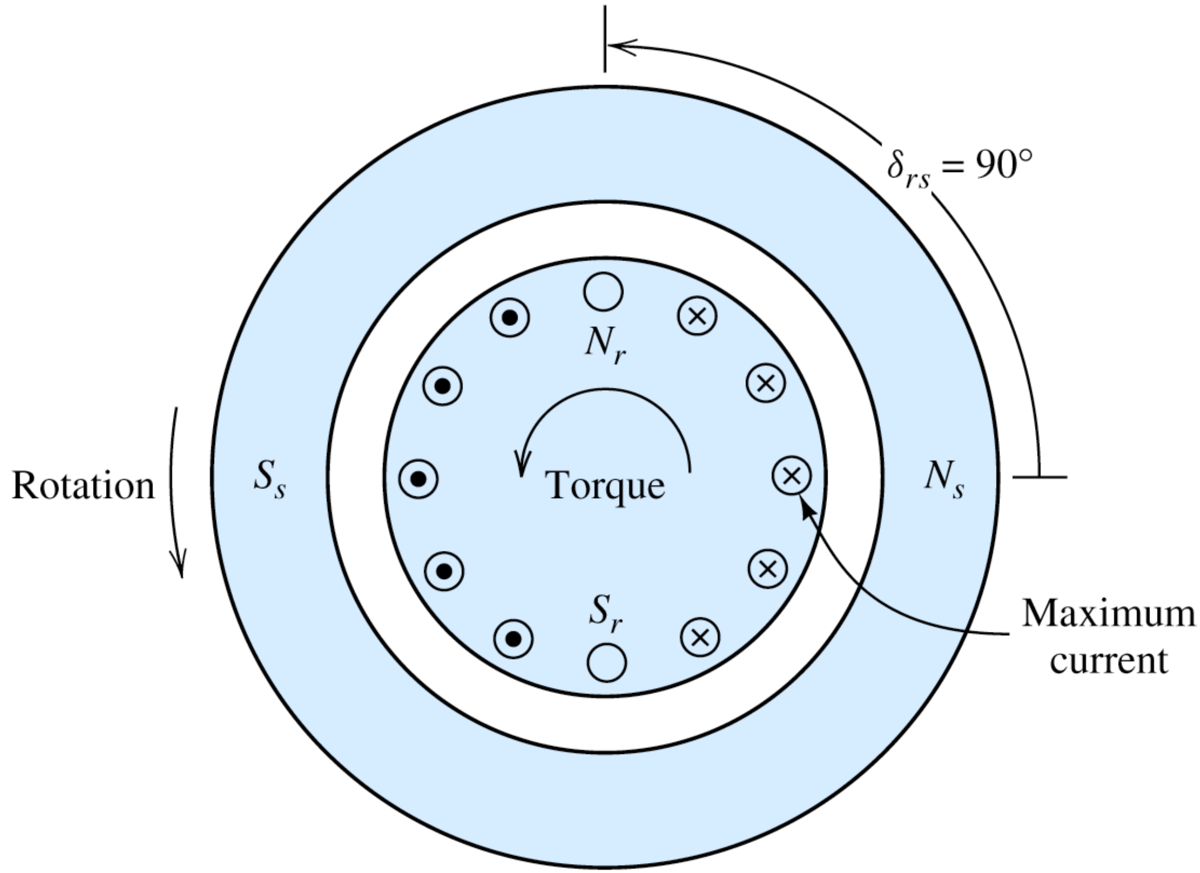
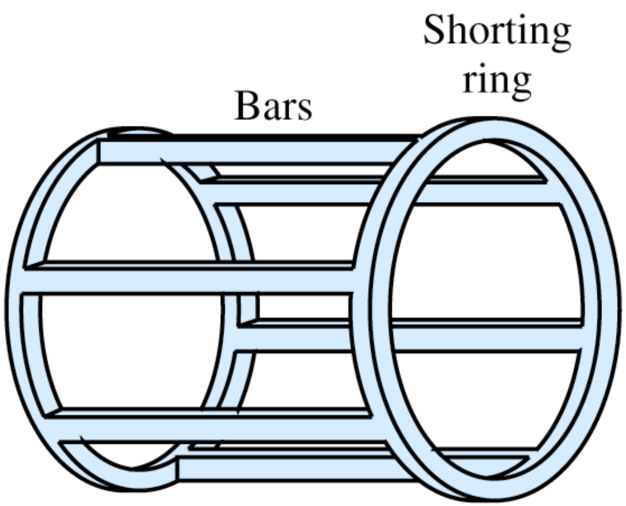
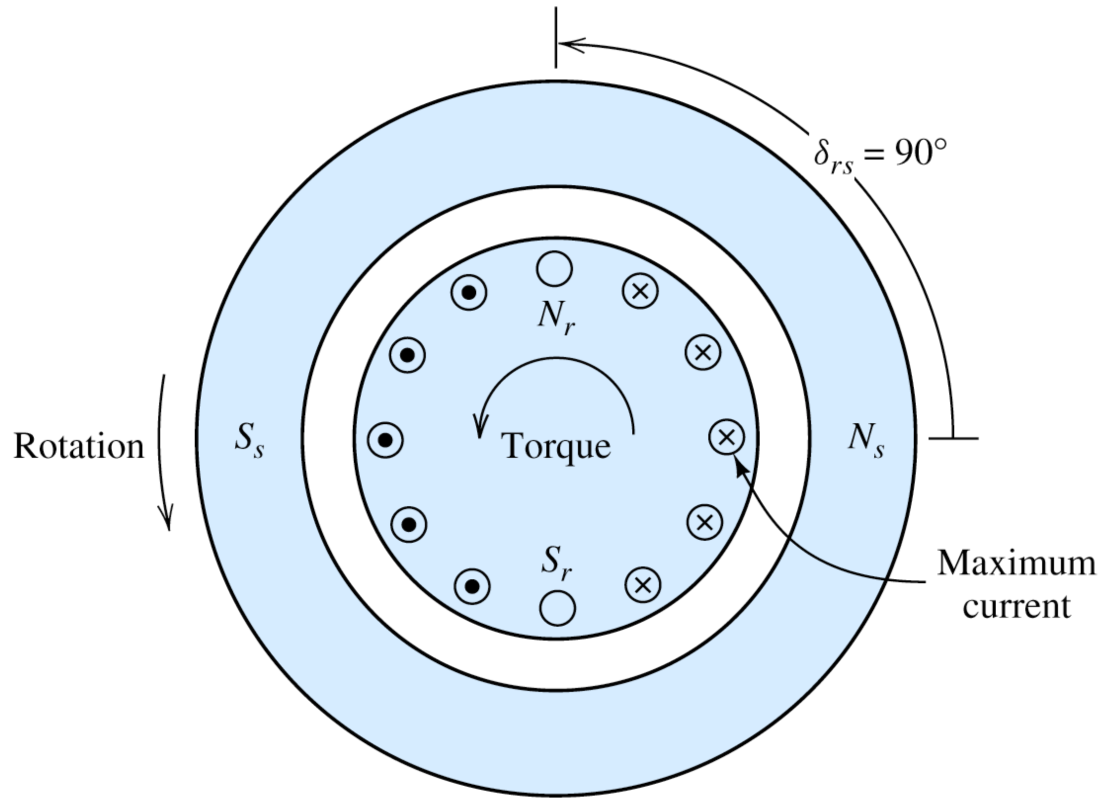


Figure 17.7 Cross section of a squirrel-cage induction motor. The rotating stator field induces currents in the conducting bars which in turn set up magnetic poles on the rotor. Torque is produced because the rotor poles are attracted to the stator poles.

Squirrel-Cage Induction Machines





Slip and Slip Frequency

$$s = \frac{\omega_s - \omega_m}{\omega_s} = \frac{n_s - n_m}{n_s}$$

$$\omega_{\mathrm{slip}} = s\omega$$

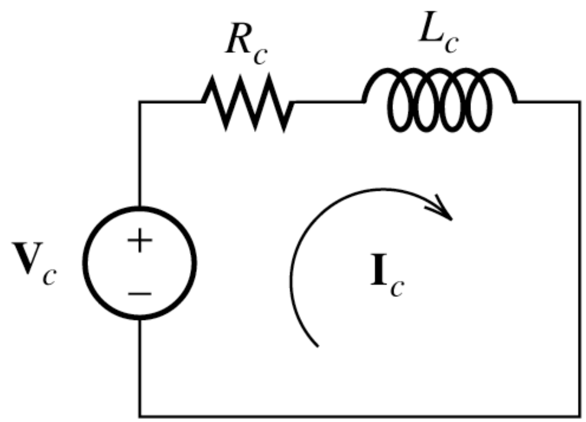
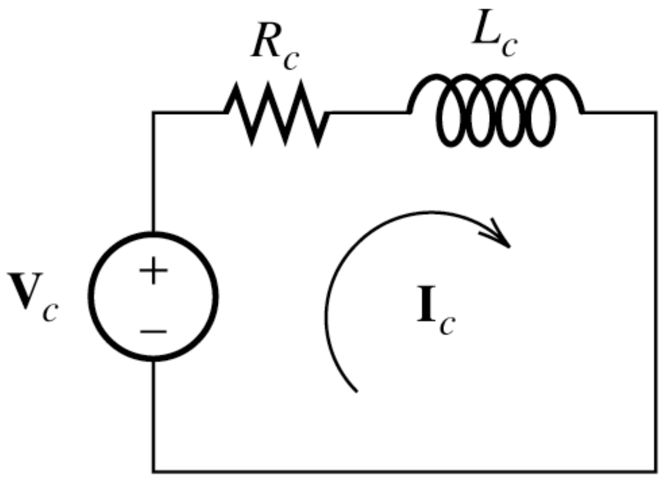


Figure 17.8 Equivalent circuit for a rotor conductor. $\mathbf{v}_c$ is the phasor for the induced voltage, R_c is the resistance of the conductor, and L_c is the inductance.

Effect of Rotor Inductance on Torque



$$\mathbf{I}_c = \frac{\mathbf{V}_c}{R_c + js\omega L_c}$$

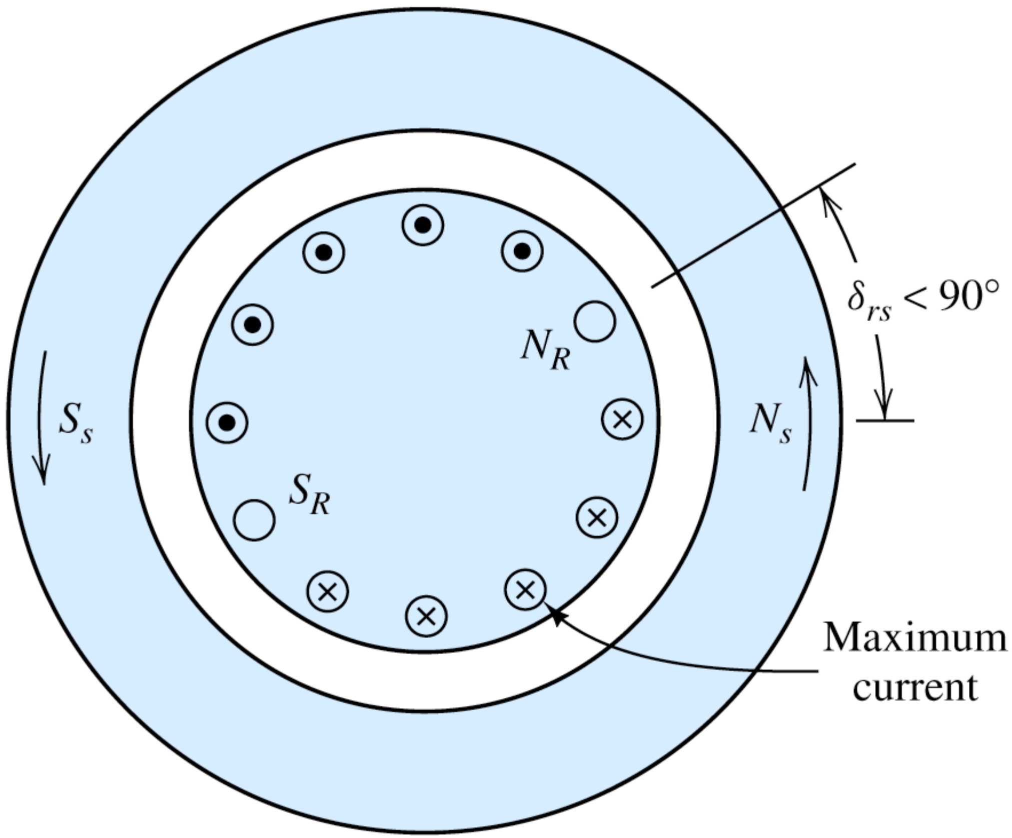
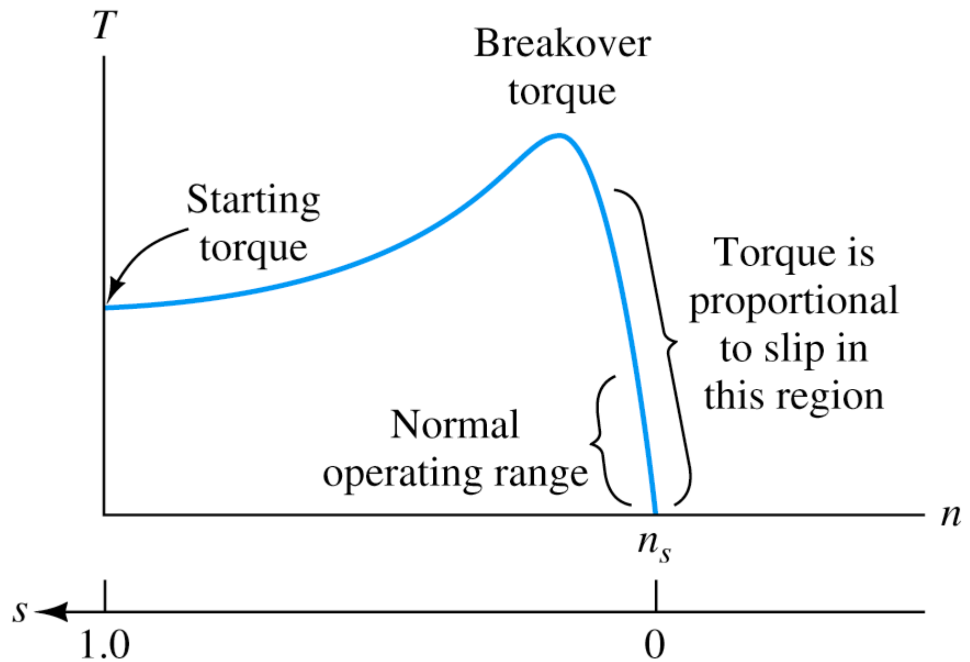


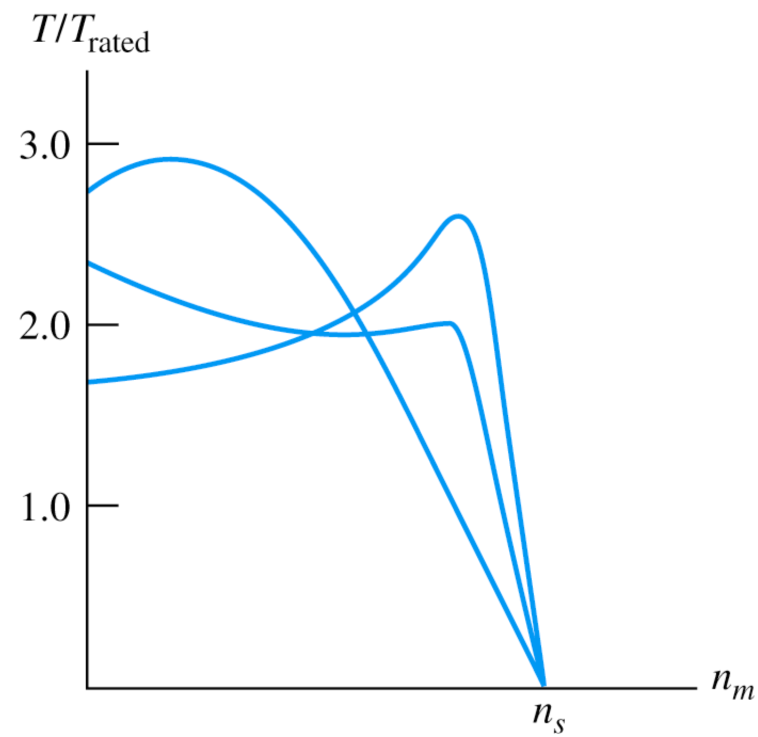
Figure 17.9 As slip s increases, the conductor currents lag the induced voltages. Consequently, the angular displacement δ_{rs} between the rotor poles and the stator poles approaches $0°$.

Torque–Speed Characteristic



For small values of slip, developed torque is proportional to slip.

Motor designers can modify the shape of the
torque–speed curve by
changing various aspects of the machine design such as the cross section and depth of the rotor conductors.



Example Exercise

- 5 hp 4 pole 60 Hz 3 phase induction motor runs at 1750 rpm under full-load. Determine the slip and the frequency of the rotor currents at full load. Also estimate the speed if load torque drops to half.

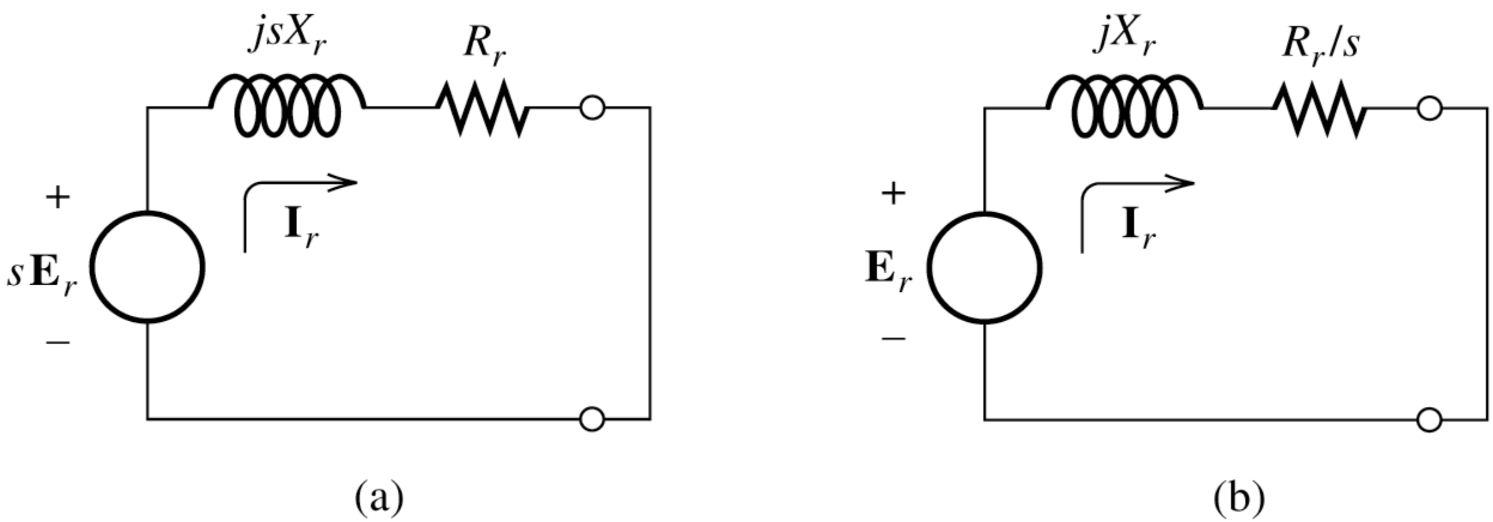


Figure 17.12 Two equivalent circuits for one phase of the rotor windings.

Induction-Motor Equivalent Circuit

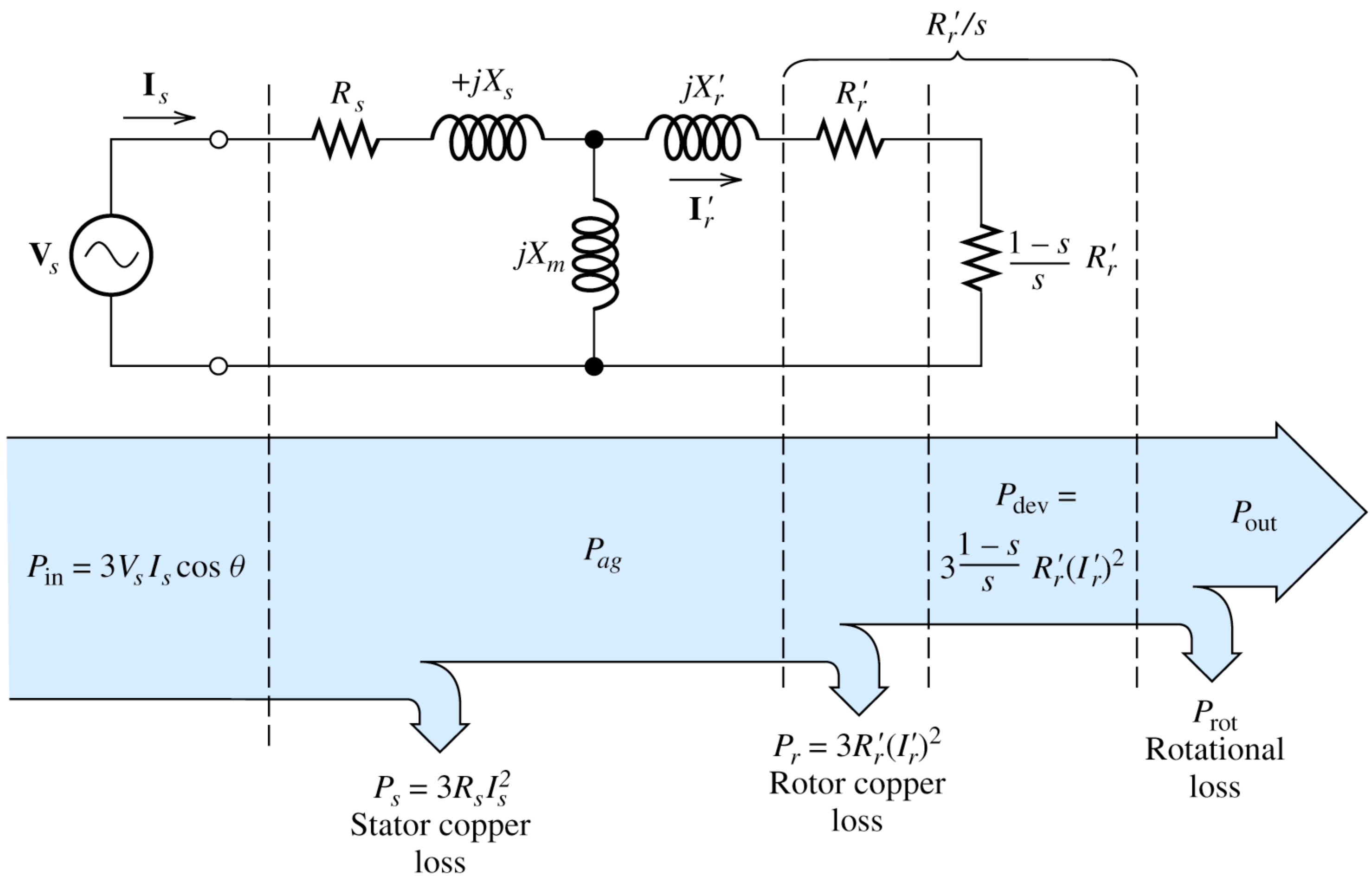


Figure 17.13 Equivalent circuit for one phase of an induction motor and the associated power-flow diagram. V_s is the rms phase voltage and I_s is the rms phase current.

Phase versus Line Quantities

The voltage V_s across each winding and current I_s through each winding shown in Figure 17.13 are called the **phase voltage** and **phase current**, respectively.

The windings of an induction motor may be connected in either a delta or a wye.

Relationships between line and phase quantities for a delta-connected motor.

$$V_s = V_{\text{line}}$$

$$I_{\text{line}} = I_s \sqrt{3}$$

Relationships between line and phase quantities for a wye-connected motor.

$$V_s = \frac{V_{\text{line}}}{\sqrt{3}}$$

$$I_{\text{line}} = I_s$$

Power and Torque Calculations

$$P_{\mathrm{dev}} = 3 \times \frac{1-s}{s} R_r' \left(I_r'\right)^2$$

$$P_r = 3R_r'\left(I_r'\right)^2$$

$$P_s = 3R_s I_s^2$$

$$P_{\text{in}} = 3 I_s V_s \cos(\theta)$$

$$P_{\text{out}} = P_{\text{dev}} - P_{\text{rot}}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

$$T_{\text{dev}} = \frac{P_{\text{dev}}}{\omega_m}$$

$$P_{\mathrm{ag}} = P_r + P_{\mathrm{dev}}$$

$$P_{\mathrm{dev}} = (1 - s) P_{\mathrm{ag}}$$

$$P_{\mathrm{ag}} = 3 \times \frac{1}{s} R_r' (I_r')^2$$

$$T_{\mathrm{dev}} = \frac{(1 - s) P_{\mathrm{ag}}}{\omega_m}$$

$$T_{\mathrm{dev}} = \frac{P_{\mathrm{ag}}}{\omega_s}$$

Example Exercise

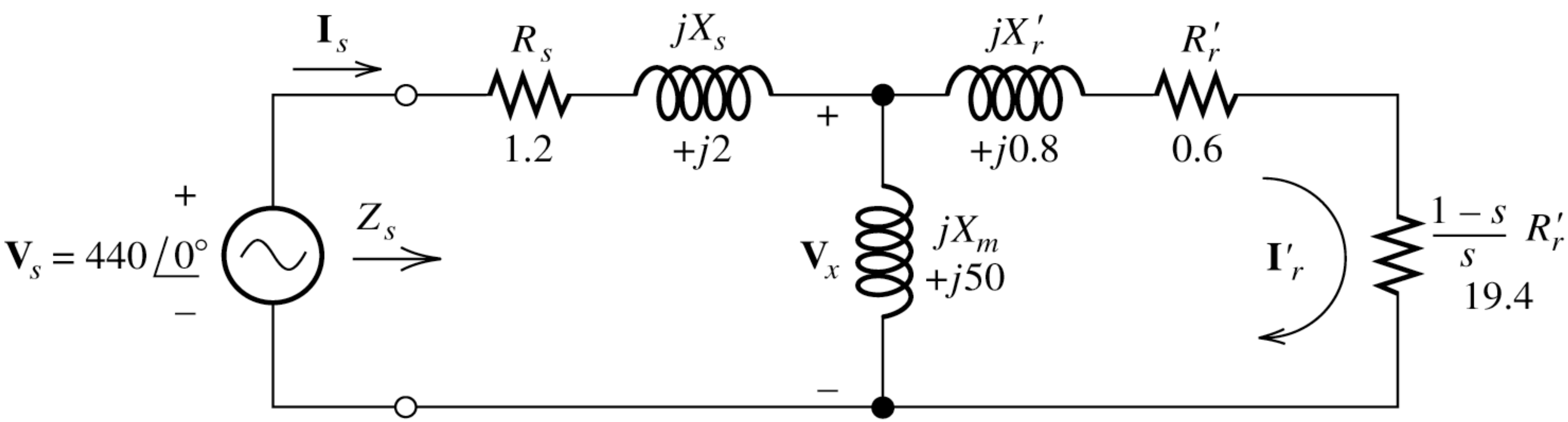


Figure 17.14 Equivalent circuit for one phase of the motor of Example 17.1.

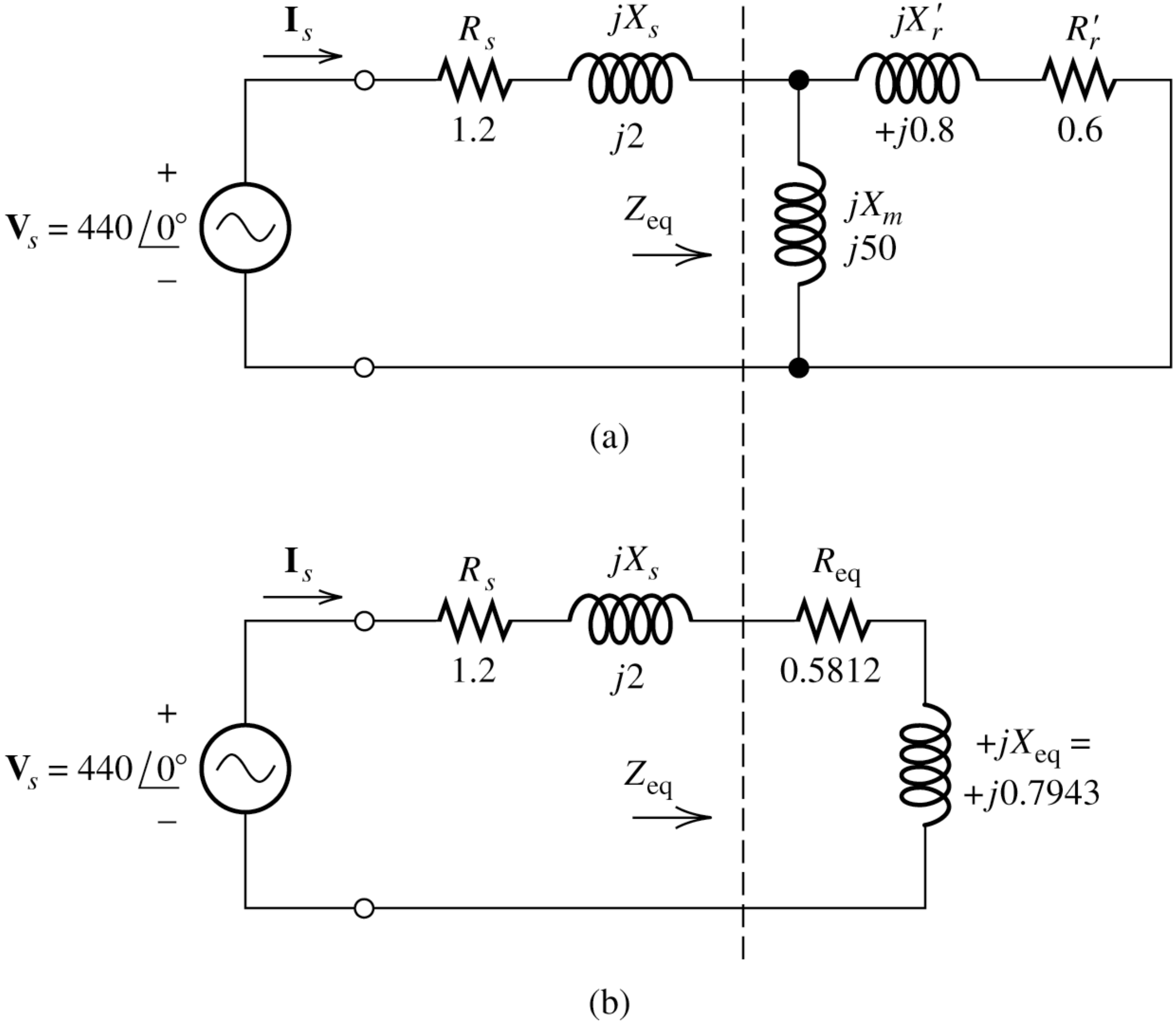


Figure 17.15 Equivalent circuit for Example 17.2.

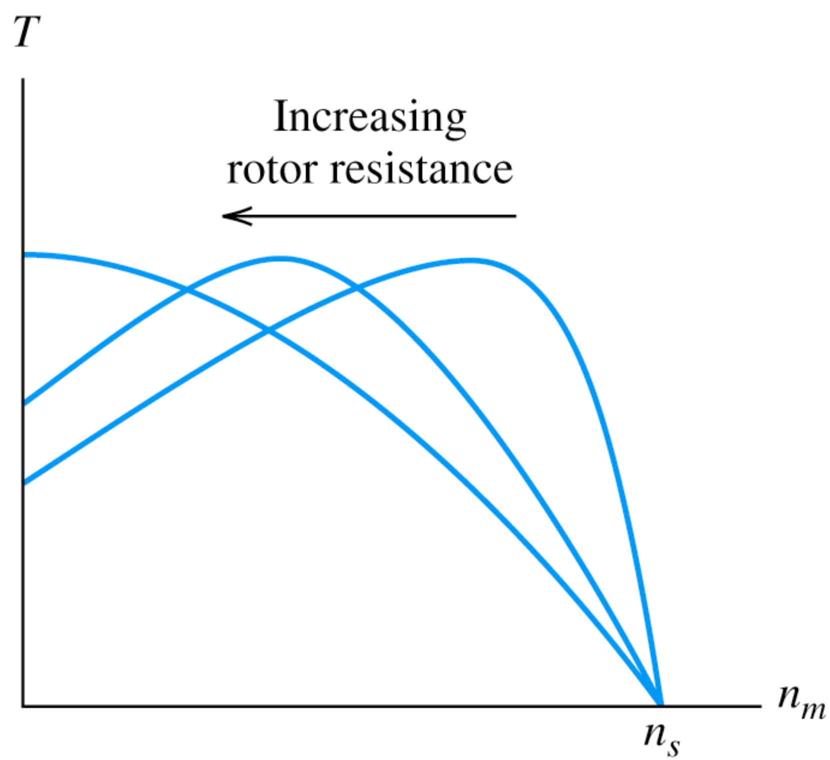
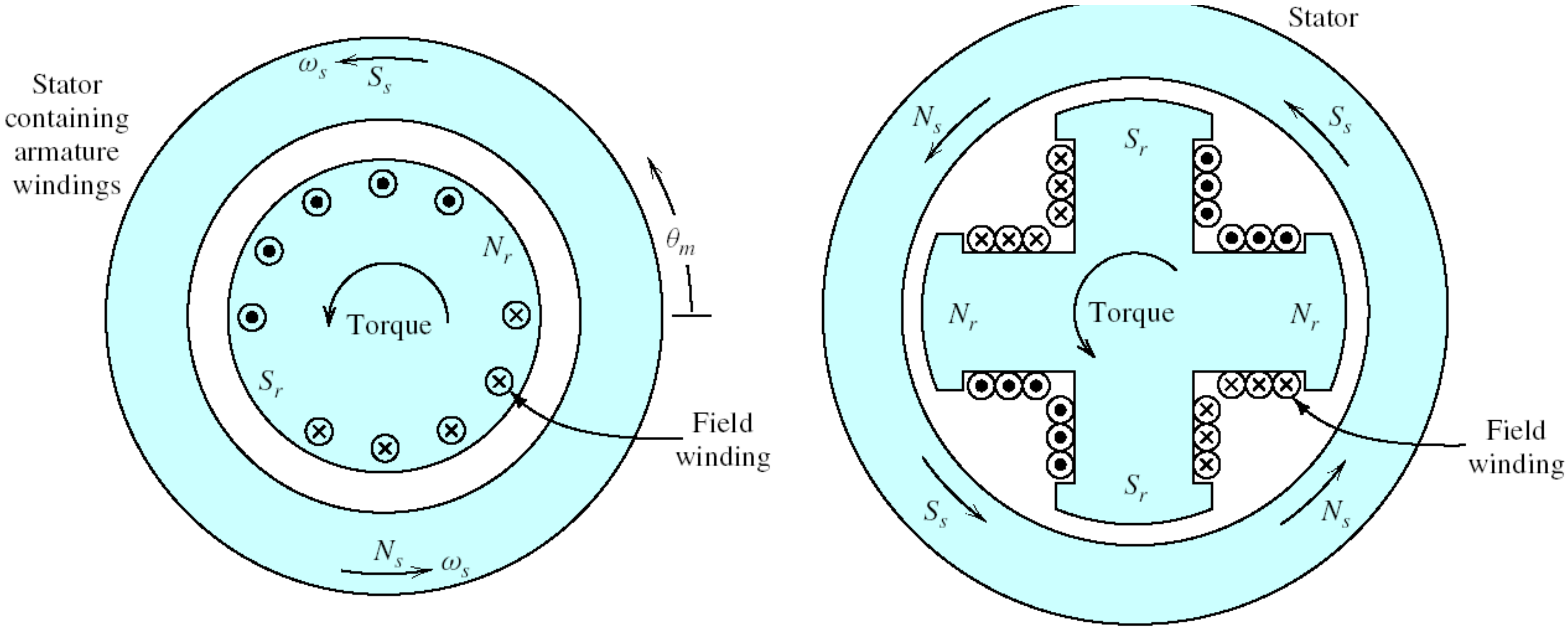


Figure 17.16 Variation of resistance in series with the rotor windings changes the torque–speed characteristic of the wound-rotor machine.

Selection of Induction Motors

Some of the most important considerations in selecting an induction motor are:

1. Efficiency
2. Starting torque
3. Pull-out torque
4. Power factor
5. Starting current



(a) Two-pole cylindrical rotor machine

(b) Four-pole salient rotor machine

Figure 17.17 Cross sections of two synchronous machines. The relative positions of the stator and rotor poles are shown for motor action. Torque is developed in the direction of rotation because the rotor poles try to align themselves with the opposite stator poles.

SYNCHRONOUS MACHINES

Generation of electrical energy by utility companies is done almost exclusively with synchronous machines.

Assuming a constant frequency source, the speed of a synchronous motor does not vary with load.

The stator windings of a synchronous machine are basically the same as those of an induction machine.