The power crossing the air gap is (three times) the power delivered to the right of the dashed line.

\[ P_{ag} = 3R_{eq} \left( I_{s, starting} \right)^2 \]

\[ = 239.72 \text{ kW} \]

Finally, the starting torque is found using Equation 17.34.

\[ T_{\text{dev, starting}} = \frac{P_{ag}}{\omega_s} \]

\[ = \frac{239.7 \times 10^3}{2\pi \times \frac{60}{3}} \]

\[ = 1907 \text{ newton meters} \]

**P17.28** Because the machine is delta connected, the magnitude of the phase current is:

\[ I_s = I_{\text{line}} / \sqrt{3} = 5.72 / \sqrt{3} = 3.3 \text{ A rms} \]

Then we have

\[ P_{\text{in}} = 3VI \cos \theta = 3(220)(3.3)(0.800) = 1742 \text{ W} \]

\[ P_{\text{out}} = 2 \times 746 = 1492 \text{ W} \]

efficiency = \( \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = 85.65\% \)

**P17.29** Because the machine is wye connected the phase voltage is:

\[ V_{\text{line}} / \sqrt{3} = 440 / \sqrt{3} = 254.0 \text{ V rms} \]

Refer to Figure 17.13.

\[ P_{\text{in}} = 3VI \cos \theta = 3(254.0)(16.8)(0.80) = 10.243 \text{ kW} \]

\[ P_{ag} = P_{\text{in}} - P_{\text{r}} = 10.243 - 0.350 = 9.893 \text{ kW} \]

\[ P_{\text{dev}} = P_{ag} - P_{\text{rot}} = 9.893 - 0.120 = 9.773 \text{ kW} \]

\[ P_{\text{out}} = P_{\text{dev}} - P_{\text{rot}} = 9.773 - 0.400 = 9.373 \text{ kW} \]

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = 91.51\% \]

**P17.30** The no-load speed is approximately 1800 rpm. Thus, the synchronous speed appears to be 1800 rpm, and we have a four-pole motor.

Steady-state operation is at the intersection of the torque-speed
characteristic of the motor and that of the load. Thus, we have

\[ T_{\text{out}} = 25 \text{ newton meters} \quad n_m = 1400 \text{ rpm} \]

The slip is:

\[ s = n_s - n_m = \frac{1800 - 1400}{1800} = 22.22\% \]

\[ \omega_m = \frac{n_m 2\pi}{60} = 146.6 \text{ radian/s} \]

\[ P_{\text{out}} = T_{\text{out}} \omega_m = 3665 \text{ W} \]

Since we are assuming \( P_{\text{rot}} = 0 \), we have

\[ P_{\text{dev}} = P_{\text{out}} = 3 \left( 1 - \frac{s}{s} \right) R_r' (I_r')^2 \]

Also, we have

\[ \rho = 3 R_r' (I_r')^2 \]

Thus,

\[ \rho = P_{\text{out}} \times \frac{s}{1 - s} = \frac{3665}{1 - 0.2222} = 1047 \text{ W} \]

P17.31 As an engineering estimate, we take the difference between the motor torque and the load torque as approximately 25 newton meters over the speed range of interest. Thus, the angular acceleration of the system is:

\[ \frac{d\omega_m}{dt} = \frac{T_{\text{motor}} - T_{\text{load}}}{\text{rotational inertia}} = \frac{25}{5} = 5 \text{ radian/s}^2 \]

\( n_m = 1000 \text{ rpm} \) corresponds to \( \omega_m = 104.7 \). Thus, the time required is approximately:

\[ T_{\text{run-up}} = \frac{104.7}{5} = 21 \text{ seconds} \]

P17.32* First, the full-load output torque is:

\[ T_{\text{out}} = \frac{P_{\text{out}}}{\omega_m} = \frac{5 \times 746}{3500(2\pi/60)} = 10.18 \text{ newton meters} \]

We assume that the developed torque is proportional to slip in the normal operating range.

\[ T_{\text{dev}} = T_{\text{out}} + T_{\text{rot}} = k \left( \frac{n_s - n_m}{n_s} \right) = K(n_s - n_m) \]

Thus at full load, we have:

\[ 10.18 + T_{\text{rot}} = K(100) \quad (1) \]
1. A very constant speed is required as the load varies.

2. It is desirable to take advantage of the power-factor correction capability of the synchronous motor.

P17.35* 1. Use an electronic system to convert 60-Hz power into three-phase ac of variable frequency. Start with a frequency of one hertz or less and then gradually increase the frequency.

2. Use a prime mover to bring the motor up to synchronous speed before connecting the source.

3. Start the motor as an induction motor relying on the amortisseur conductors to produce torque.

P17.36 A synchronous capacitor is an overexcited three-phase synchronous motor operating with no load. It acts as a source of reactive power and can correct the overall power factor of an industrial plant, thereby reducing energy costs.

P17.37 See Figure 17.23 in the text for the V curves. The phasor diagram corresponding to the minimum point of a curve is:

\[
\begin{align*}
\mathbf{I}_a & \quad \mathbf{V}_a \\
\mathbf{E}_r & \quad jX_s \mathbf{I}_a
\end{align*}
\]

P17.38* (a) Field current remains constant. The field circuit is independent of the ac source and the load.

(b) Mechanical speed remains constant assuming that the pull-out torque has not been exceeded.

(c) Output torque increases by a factor of \(1/0.75 = 1.333\).

(d) Armature current increases in magnitude.

(e) Power factor decreases and becomes lagging.

(f) Torque angle increases.
P17.39  (a) Output power remains constant.
(b) Mechanical speed remains constant.
(c) Output torque remains constant.
(d) Armature current increases in magnitude and its phase leads the source voltage.
(e) Power factor decreases and becomes leading. Reactive power is produced by the machine.
(f) Torque angle decreases.

P17.40  Synchronous speed for the machine is:
\[
\omega_s = \frac{\omega}{(P/2)} = \frac{2\pi 60}{6/2} = 125.7 \text{ rad/s}
\]
\[
n_s = 1200 \text{ rpm}
\]
\[
T_{dev} = \frac{P_{dev}}{\omega_s} = 29.68 \text{ Nm}
\]
According to Equation 17.37, we have:
\[
T_{dev} = KB_r B_{total} \sin \delta
\]

We define \( K_r = KB_r B_{total} \). Then from the initial operating conditions, we find:
\[
K_r = \frac{T_{dev}}{\sin \delta} = \frac{29.68}{\sin(5^\circ)} = 340.6
\]

Now when the torque doubles, we have
\[
\sin \delta = \frac{T_{\text{dev}}}{K_r} = \frac{2 \times 29.68}{340.6}
\]
which yields \( \delta = 10.04^\circ \).

The pullout torque occurs for \( \delta = 90^\circ \). Thus we have:
\[
T_{\text{max}} = K_r \sin(90^\circ) = 340.6 \text{ newton meters}
\]
\[
P_{\text{dev, max}} = T_{\text{max}} \omega_s = 42.82 \text{ kW or 57.39 hp}
\]

P17.41*  \[
\omega_s = \frac{\omega}{(P/2)} = \frac{2\pi 60}{10/2} = 75.40 \text{ rad/s}
\]
\[
n_s = 720 \text{ rpm}
\]
\[
T_{\text{dev, rated}} = \frac{P_{\text{dev, rated}}}{\omega_s} = \frac{100 \times 746}{75.40} = 989.4 \text{ newton meters}
\]
P17.45  (a)  \[ \omega_s = \frac{\omega}{(P/2)} = \frac{2\pi \times 60}{6/2} = 125.66 \text{ rad/s} \quad n_s = 1200 \text{ rpm} \]

\[ T_{\text{dev}} = \frac{P_{\text{dev}}}{\omega_s} = \frac{50 \times 746}{125.66} = 296.8 \text{ newton meters} \]

(b)  \[ P_m = P_{\text{dev}} = 50 \times 746 = 3I_aV_a \cos \theta = 3I_a240(0.9) \]

Thus,  \( I_a = 57.56 \).

\[ \theta = \cos^{-1}(0.9) = 25.84^\circ. \]

Thus,  \( I_a = 57.56\angle 25.84^\circ \)

\[ E_{r1} = V_a - jX_sI_a = 240 - j0.5I_a = 240 - j0.5(51.80 + j25.21) \]

\[ E_{r2} = 252.6 - j25.90 = 253.9\angle -5.85^\circ \]

Thus, the torque angle is  \( \delta_1 = 5.85^\circ. \)

(c)  To double the power, we must double the torque. According to Equation 17.37, the developed torque is proportional to  \( \sin \delta \).

Thus,

\[ \frac{\sin \delta_2}{\sin \delta_1} = 2 \]

which yields the new torque angle  \( \delta_2 = 11.77^\circ. \)  \( E_r \) remains constant in magnitude, thus we have

\[ E_{r2} = 253.9\angle -11.77^\circ \]

\[ I_a = \frac{V_a - E_{r2}}{jX_s} = \frac{240 - 253.9\angle -11.77^\circ}{j0.5} = 105.0\angle 9.38^\circ \]

The power factor is  \( \cos(9.38^\circ) = 98.66\% \) leading.

P17.46  Because the developed power includes the losses, we have:

\[ P_m = P_{\text{dev}} = 100 \times 746 = 74600 \text{ W} = 3I_aV_a \cos \theta_1 \]

Solving, we have

\[ I_a = \frac{P_m}{3V_a \cos \theta_1} = \frac{74600}{3(240)0.85} = 121.9 \text{ A} \]

\[ \theta_1 = \cos^{-1}(0.85) = 31.79^\circ \]

Thus,

\[ I_a = 121.9\angle -31.79^\circ \]
\[ E_{r1} = V_a = jX_s I_{a1} = 207.9 - j51.81 = 214.3 \angle -13.99^\circ \]

The phasor diagram is:

For 100\% power factor, the phasor diagram becomes:

Notice that (refer to Figure 17.22) the imaginary (i.e., vertical) component of \( E_r \) is the same in both diagrams. Thus we have:

\[ X_s I_{a2} = E_{r1} \sin(13.99^\circ) = 51.81 \]

\[ E_{r2} = \sqrt{(V_a)^2 + (X_s I_{a2})^2} = \sqrt{240^2 + (51.81)^2} = 245.5 \]

The magnitude of \( E_r \) is proportional to the field current, so we have:

\[ I_{f2} = I_{f1} \frac{E_{r2}}{E_{r1}} = 10 \times \frac{245.5}{214.3} = 11.46 \text{ A} \]

**P17.47** (a) The speed of a synchronous machine is related to the frequency of the armature voltages by Equation 17.14:

\[ n_s = \frac{120f}{p} \]

The frequency of the voltage applied to the 12-pole motor is 60 Hz and the speed is 600 rpm. Thus, the generator is driven at 600 rpm and the voltages induced in its armature have a frequency of:

\[ f_{gen} = \frac{n_s p_{gen}}{120} = \frac{600 \times 10}{120} = 50 \text{ Hz} \]
current. The setting required would change with load.

**P17.49** The machine has copper-losses in the armature windings and rotational losses. (We do not consider the power that must be supplied to the field circuit.) With no load and current adjusted for minimum armature current, the machine operates with unity power factor. For a delta connection, the phase current is the line current divided by $\sqrt{3}$. The input power is:

$$P_{\text{in, no-load}} = 3(480)(9.5) = 13.68 \text{ kW}$$

The copper loss is:

$$P_{\text{copper, no-load}} = 3(0.05)(9.5)^2 = 13.5 \text{ W}$$

Thus, the rotational loss is:

$$P_{\text{rot}} = P_{\text{in, no-load}} - P_{\text{copper, no-load}} = 13.68 \text{ kW}$$

We assume that the rotational loss is independent of the load. At full-load, we have:

$$P_{\text{out}} + P_{\text{rot}} + 3(I_a)^2 R_a = 3V_a I_a \cos(\theta) = P_{\text{in}}$$

$$200(746) + 13680 + 0.15(I_a)^2 = 3(480)I_a(0.9)$$

Solving for $I_a$, we have:

$$I_a = 127.6 \text{ or } 8510$$

The appropriate root is $I_a = 127.6 \text{ A}$. Thus, we have:

$$P_{\text{in}} = 3V_a I_a \cos(\theta) = 165.4 \text{ kW}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = 90.22\%$$

**P17.50** (a)

$$P_{\text{in}} = \frac{P_{\text{out}}}{\eta} = \frac{746}{0.8} = 932.5 \text{ W}$$

$$\text{power factor} = \cos(\theta) = \frac{P_{\text{in}}}{V I} = \frac{932.5}{120(10.2)} = 76.2\%$$

Of course, the power factor is lagging for an induction motor.

(b) $Z = (V/I) \angle \cos^{-1}(\text{power factor})$

$$= 120/10.2 \angle \cos^{-1}(0.762)$$

$$= 11.76 \angle 40.36^\circ \Omega$$

(c) Since the motor runs just under 1800 rpm, evidently we have a four-pole motor.