in \( v_c = 0 \). Because the induced voltages are zero, the rotor currents are zero. Thus, the forces acting on the rotor conductors, given by \( f = i l \times B \), are zero.

**P17.4** At 60 Hz, synchronous speed for a six-pole machine is:

\[
ns = \frac{120f}{\rho} = \frac{120(60)}{6} = 1200 \text{ rpm}
\]

The slip is given by:

\[
s = \frac{ns - nm}{ns} = \frac{1200 - 1160}{1200} = 3.33\%
\]

The frequency of the rotor currents is the slip frequency. From Equation 17.17, we have \( \omega_{slip} = s\omega \). For frequencies in the Hz, this becomes:

\[
f_{slip} = sf = 0.0333 \times 60 = 2 \text{ Hz}
\]

In the normal range of operation, slip is approximately proportional to output power and torque. Thus at half power, we estimate that \( s = 3.33/2 = 1.67\% \). This corresponds to a speed of 1180 rpm.

**P17.5** In this case the developed torque opposes the direction of rotation. Power is taken from the prime mover and converted to electrical form. Thus the machine acts as a generator.
As frequency is reduced, the reactances $X_s, X_m,$ and $X'_r$ of the machine become smaller. (Recall that $X = \omega L$.) Thus the applied voltage must be reduced to keep the currents from becoming too large, resulting in magnetic saturation and overheating.

The total field in the machine is the sum of the fields produced by the separate windings. Thus,

$$B = B_a + B_b = K_i_a(t)\cos(\theta) + K_i_b(t)\cos(\theta - 90')$$

Substituting the expressions given for the currents, we have:

$$B = KI_m\cos(\omega t)\cos(\theta) + KI_m\cos(\omega t - 90')\cos(\theta - 90')$$

Using the trigonometric identity $\cos A\cos B = \frac{1}{2}\left[\cos(A - B) + \cos(A + B)\right]$, we have:

$$B = KI_m\cos(\omega t - \theta) + \frac{KI_m}{2}\left[\cos(\omega t + \theta) + \cos(\omega t + \theta - 180')\right]$$

However, we can write $\cos(\omega t + \theta) + \cos(\omega t + \theta - 180') = 0$ because the two terms are out of phase. Thus, we have:

$$B = KI_m\cos(\omega t - \theta)$$

According to this result, the maximum flux occurs for $\theta = \omega t$, which implies rotation of the field in the counterclockwise direction at an angular speed of $\omega$. The maximum flux density is $B_{\text{max}} = KI_m$.

With the connections to the b-winding reversed the currents become

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

and

$$i_b(t) = -I_m\cos(\omega t - 90') = I_m\cos(\omega t + 90')$$

As before, the total field in the machine is the sum of the fields produced by the separate windings. Thus,

$$B = B_a + B_b = K_i_a(t)\cos(\theta) + K_i_b(t)\cos(\theta - 90')$$

Substituting the expressions given for the currents, we have:

$$B = KI_m\cos(\omega t)\cos(\theta) + KI_m\cos(\omega t + 90')\cos(\theta - 90')$$

Using the trigonometric identity $\cos A\cos B = \frac{1}{2}\left[\cos(A - B) + \cos(A + B)\right]$, we have:

$$B = KI_m\cos(\omega t + \theta) + \frac{KI_m}{2}\left[\cos(\omega t - \theta) + \cos(\omega t - \theta + 180')\right]$$

However, we can write $\cos(\omega t - \theta) + \cos(\omega t - \theta + 180') = 0$ because the
\[
\begin{align*}
\pi &= \frac{4359}{2 \pi 60/2} \\
&= 23.13 \text{ newton meters}
\end{align*}
\]

Comparing these results to those of the example, we see that the starting torque is reduced by a factor of \(163.1/23.1 = 7.06\). Depending on the torque--speed characteristic of the load, the system may not start.

**P17.22** Following the solution to Example 17.1, we have:

\[
s = \frac{n_s - n_m}{n_s} = \frac{1800 - 1728}{1800} = 0.04
\]

The per phase equivalent circuit is:

\[
\begin{align*}
Z_s &= 1.0 + j1.5 + \frac{j40(0.5 + 12 + j0.8)}{j40 + 0.5 + 12 + j0.8} \\
&= 11.98 + j5.649 \\
&= 13.25 \angle 25.24^\circ \\
\text{power factor} &= \cos(25.24^\circ) = 90.45\% \text{ lagging}
\end{align*}
\]

\[
I_s = \frac{V_s}{Z_s} = \frac{240 \angle 0^\circ}{13.25 \angle 25.24^\circ} = 18.11 \angle -25.24^\circ
\]

\[
R_m = 3 I_s V_s \cos \theta = 11.80 \text{ kW}
\]

Next, we compute \(V_x\) and \(I_x\).

\[
V_x = I_s \frac{j40(0.5 + 12 + j0.8)}{j40 + 0.5 + 12 + j0.8}
\]

\[
= 212.0 - j16.85
\]

\[
= 212.7 \angle -4.545^\circ
\]
The copper losses in the stator and rotor are:
\[ P_s = 3R_sI_s^2 = 3(1)(18.11)^2 = 983.9 \text{ W} \]

and
\[ P_r = 3R'(I'_r)^2 = 3(0.5)(16.98)^2 = 432.5 \text{ W} \]

Finally, the developed power is:
\[ P_{\text{dev}} = 3 \times \frac{1-s}{s} R'(I'_r)^2 = 10.38 \text{ kW} \]

The output torque is:
\[ T_{\text{out}} = \frac{P_{\text{out}}}{\omega_m} = 56.25 \text{ newton meters} \]

The efficiency is:
\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = 86.29\% \]

**P17.23** Neglecting rotational losses, the slip is zero with no load, and the motor runs at synchronous speed which is 1800 rpm. Then the equivalent circuit becomes:
\[ Z_s = R_s + jX_s + jX_m = 1 + j1.5 + j40 \]
\[ = 41.51 \angle 88.61^\circ \]

The power factor is:
\[ \cos(88.61^\circ) = 2.409\% \]

The current is:
\[ I_s = \frac{V_s}{Z_s} = \frac{240}{41.51 \angle 88.61^\circ} = 5.783 \angle -88.61^\circ \]

Because the machine is delta connected, the line current magnitude is
\[ I_{line} = \sqrt{3}I_s = 10 \text{ A rms} \]

P17.24 This is similar to Example 17.2. The equivalent circuit is:

\[ Z_{eq} = R_{eq} + jX_{eq} = \frac{j40(0.5 + j0.8)}{j40 + 0.5 + j0.8} = 0.4805 + j0.7902 \]

The impedance seen by the source is:
\[ Z_s = 1.0 + j1.5 + Z_{eq} \]
\[ = 1.0 + j1.5 + 0.4805 + j0.7902 \]
\[ = 2.727 \angle 57.12^\circ \]

Thus, the starting current is:
\[ I_{s, \text{starting}} = \frac{V_s}{Z_s} = 240 \angle 0^\circ \]
\[ \frac{2.727 \angle 57.12^\circ}{Z_s} \]
\[ I_{s, \text{starting}} = 88.01 \angle -57.12^\circ \]

Because the machine is delta connected, the magnitude of the starting line current is
\[ I_{linr, \text{starting}} = I_{s, \text{starting}} \sqrt{3} = 88.01 \sqrt{3} = 152.4 \text{ A rms} \]
The power crossing the air gap is (three times) the power delivered to the right of the dashed line.

\[ P_{ag} = 3R_{eq}(I_{s,\text{starting}})^2 \]
\[ = 11.17 \text{ kW} \]

Finally, the starting torque is found using Equation 17.34.

\[ T_{\text{dev, starting}} = \frac{P_{ag}}{\omega_s} \]
\[ = \frac{11170}{2\pi 60/2} \]
\[ = 59.26 \text{ newton meters} \]

**P17.25** This is similar to Problem P17.22 and Example 17.1. The per phase equivalent circuit is:

\[ Z_s = 0.08 + j0.20 + \frac{j7.5(0.06 + 1.44 + j0.15)}{j7.5 + 0.06 + 1.44 + j0.15} \]
\[ = 1.468 + j0.6193 \]
\[ = 1.594 \angle 22.87^\circ \]

Power factor = \( \cos(22.87^\circ) = 92.14\% \) lagging

\[ I_s = \frac{V_s}{Z_s} = \frac{440 \angle 0^\circ}{1.594 \angle 22.87^\circ} = 276.0 \angle -22.87^\circ \]

\[ P_{in} = 3I_sV_s \cos \theta = 335.8 \text{ kW} \]

Next, we compute \( V_x \) and \( I'_r \).

\[ V_x = I_s \frac{j7.5(0.06 + 1.44 + j0.15)}{j7.5 + 0.06 + 1.44 + j0.15} \]
\[ = 398.2 - j42.30 \]