CHAPTER 16

Exercises

E16.1 The input power to the dc motor is

$$P_{in} = V_{source} I_{source} = P_{out} + P_{loss}$$

Substituting values and solving for the source current we have

$$220 I_{source} = 50 \times 746 + 3350$$

$$I_{source} = 184.8 \text{ A}$$

Also we have

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{50 \times 746}{50 \times 746 + 3350} = 91.76\%$$

$$\text{speed regulation} = \frac{n_{no-load} - n_{full-load}}{n_{full-load}} \times 100\%$$

$$= \frac{1200 - 1150}{1150} \times 100\% = 4.35\%$$

E16.2 (a) The synchronous motor has zero starting torque and would not be able to start a high-inertia load.

(b) The series-field dc motor shows the greatest amount of speed variation with load in the normal operating range and thus has the poorest speed regulation.

(c) The synchronous motor operates at fixed speed and has zero speed regulation.

(d) The ac induction motor has the best combination of high starting torque and low speed regulation.

(e) The series-field dc motor should not be operated without a load because its speed becomes excessive.

E16.3 Repeating the calculations of Example 16.2, we have

(a) $$i_A(0+) = \frac{V_T}{R_A} = \frac{2}{0.05} = 40 \text{ A}$$

$$f(0+) = Bl i_A(0+) = 2(0.3)40 = 24 \text{ N}$$

$$u = \frac{V_T}{Bl} = \frac{2}{2(0.3)} = 3.333 \text{ m/s}$$

(b) $$i_A = \frac{f_{load}}{Bl} = \frac{4}{2(0.3)} = 6.667 \text{ A}$$

$$e_A = V_T - R_A I_A = 2 - 0.05(6.667) = 1.667 \text{ V}$$

$$u = \frac{e_A}{Bl} = \frac{1.667}{2(0.3)} = 2.778 \text{ m/s}$$

$$p_m = f_{load} u = 4(2.778) = 11.11 \text{ W}$$

$$p_R = i_A^2 R = 2.222 \text{ W}$$

$$p_t = V_T i_A = 2(6.667) = 13.33 \text{ W}$$

$$\eta = \frac{p_m}{p_t} \times 100\% = \frac{11.11}{13.33} = 83.33\%$$

(c)

$$i_A = \frac{f_{pull}}{Bl} = \frac{2}{2(0.3)} = 3.333 \text{ A}$$

$$e_A = V_T + R_A I_A = 2 + 0.05(3.333) = 2.167 \text{ V}$$

$$u = \frac{e_A}{Bl} = \frac{2.167}{2(0.3)} = 3.611 \text{ m/s}$$

$$p_m = f_{pull} u = 2(3.611) = 7.222 \text{ W}$$

$$p_t = V_T i_A = 2(3.333) = 6.667 \text{ W}$$

$$p_R = i_A^2 R = 0.5555 \text{ W}$$

$$\eta = \frac{p_t}{p_m} \times 100\% = \frac{6.667}{7.222} = 92.31\%$$

E16.4 Referring to Figure 16.15 we see that $E_A \cong 125$ V for $I_F = 2$ A and $n = 1200$. Then for $n = 1500$, we have

$$E_A = 125 \times \frac{1500}{1200} = 156 \text{ V}$$

E16.5 Referring to Figure 16.15 we see that $E_A \cong 145$ V for $I_F = 2.5$ A and $n = 1200$. Then for $n = 1500$, we have

$$E_A = 145 \times \frac{1500}{1200} = 181.3 \text{ V}$$

$$\omega_m = n \times \frac{2\pi}{60} = 157.1 \text{ rad/s}$$

$$T_{dev} = \frac{P_{dev}}{\omega_m} = \frac{10 \times 746}{157.1} = 47.49 \text{ Nm}$$

$$I_A = \frac{P_{dev}}{E_A} = \frac{10 \times 746}{181.3} = 41.15 \text{ A}$$

$$V_T = E_A + R_A I_A = 181.3 + 0.3(41.15) = 193.6 \text{ V}$$

E16.6 $R_{adj} = \frac{V_T - R_F I_F}{I_F} = \frac{300 - 10 \times 10}{10} = 20\ \Omega$

Because I_F remains constant the value of $K\varphi$ is the same value as in Example 16.4, which is 2.228. Furthermore the loss torque also remains constant at 11.54 Nm, and the developed torque remains at 261.5 Nm. Thus the armature current is still 117.4 A. Then we have

$$E_A = V_T - R_A I_A = 300 - 0.065(117.4) = 292.4\ \text{V}$$

$$\omega_m = \frac{E_A}{K\varphi} = \frac{292.4}{2.228} = 131.2\ \text{rad/s}$$

$$n_m = \omega_m \frac{60}{2\pi} = 1253\ \text{rpm}$$

Thus the motor speeds up when V_T is increased.

E16.7 Following Example 16.4, we have

$$I_F = \frac{V_T}{R_F + R_{adj}} = \frac{240}{10 + 30} = 6\ A$$

Referring to Figure 16.18 we see that $E_A \cong 200$ V for $I_F = 6$ A and $n = 1200$. Thus we have

$$K\varphi = \frac{E_A}{\omega_m} = \frac{200}{1200(2\pi / 60)} = 1.592$$

$$I_A = \frac{T_{dev}}{K\varphi} = \frac{261.5}{1.592} = 164.3\ A$$

$$E_A = V_T - R_A I_A = 240 - 0.065(164.3) = 229.3\ \text{V}$$

$$\omega_m = \frac{E_A}{K\varphi} = \frac{229.3}{1.592} = 144.0\ \text{rad/s}$$

$$n_m = \omega_m \frac{60}{2\pi} = 1376\ \text{rpm}$$

$$P_{out} = T_{out}\omega_m = 36\ \text{kW}$$

$$P_{in} = V_T(I_F + I_A) = 240(6 + 164.3) = 40.87\ \text{kW}$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = 88.08\%$$

E16.8

$$\omega_{m3} = \omega_{m1}\sqrt{\frac{T_{dev1}}{T_{dev3}}} = 125.7\sqrt{\frac{12}{6}} = 177.8\ \text{rad/s}$$

$$n_{m3} = \omega_{m3} \frac{60}{2\pi} = 1698\ \text{rpm}$$

$$P_{out3} = T_{out3}\omega_{m3} = 1066\ \text{W}$$

E16.9 With R_A = 0 and fixed V_T, the shunt motor has constant speed independent of the load torque. Thus we have

$$n_{m2} = n_{m1} = 1200 \text{ rpm}$$
$$\omega_{m2} = \omega_{m1} = 125.7 \text{ rad/s}$$
$$P_{out1} = T_{out1}\omega_{m1} = 1508 \text{ W}$$
$$P_{out2} = T_{out2}\omega_{m2} = 3016 \text{ W}$$

E16.10 Decreasing V_T decreases the field current and therefore the flux φ. In the linear portion of the magnetization curve, flux is proportional to the field current. Thus reduction of V_T leads to reduction of φ and according to Equation 16.35, the speed remains constant. (Actually, some speed variation will occur due to saturation effects.)

E16.11 The torque--speed relationship for the separately excited machine is given by Equation 16.27

$$T_{dev} = \frac{K\varphi}{R_A}(V_T - K\varphi\omega_m)$$

which plots as a straight line in the T_{dev} - ω_m plane. A family of plots for various values of V_T is shown in Figure 16.27 in the book.

E16.12 The torque--speed relationship for the separately excited machine is given by Equation 16.27

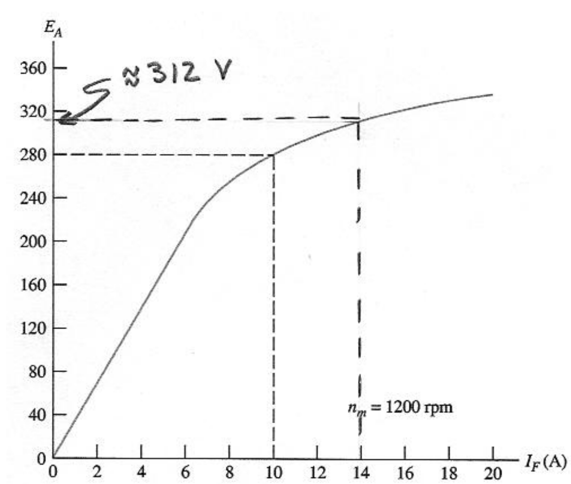
$$T_{dev} = \frac{K\varphi}{R_A}(V_T - K\varphi\omega_m)$$

which plots as a straight line in the T_{dev} - ω_m plane. As the field current is increased, the flux φ increases. A family of plots for various values of I_F and φ is shown in Figure 16.28 in the book.

E16.13

$$I_F = \frac{V_F}{R_{\text{adj}} + R_F} = \frac{140}{0+10} = 14 \text{ A}$$

$$V_{NL} = E_A = 312\frac{1000}{1200} = 260 \text{ V}$$



$$V_{FL} = E_A - R_A I_A = 260 - 200 \times 0.065 = 247 \text{ V}$$

$$\text{voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \frac{260 - 247}{247} \times 100\% = 5.26\%$$

$$P_{\text{out}} = I_L V_{FL} = 200 \times 247 = 49.4 \text{ kW}$$

$$P_{\text{dev}} = P_{\text{out}} + R_A I_A^2 = 49400 + 0.065(200)^2 = 52.0 \text{ kW}$$

$$\omega_m = n_m \frac{2\pi}{60} = 104.7 \text{ rad/sec} \qquad P_{\text{in}} = \frac{P_{\text{out}}}{0.85} = \frac{49.4}{0.85} = 58.1 \text{ kW}$$

$$P_{\text{losses}} = P_{\text{in}} - P_{\text{dev}} = 58.1 - 52.0 = 6.1 \text{ kW}$$

$$T_{\text{in}} = \frac{P_{\text{in}}}{\omega_m} = \frac{58100}{104.7} = 555 \text{ nm} \qquad T_{\text{dev}} = \frac{P_{\text{dev}}}{\omega_m} = \frac{52000}{104.7} = 497 \text{ nm}$$

Answers for Selected Problems

P16.5* Two disadvantages of dc motors compared to signal-phase ac induction motors for a ventilation fan, which we can expect to operate most of the time, are first that dc power is usually not readily available in a home and second that dc machines tend to require more frequent maintenance than ac induction motors.

P16.8* $\text{speed regulation} = 2.27\%$

P16.11* $T_{\text{start}} = 50.9 \text{ Nm}$

P16.17* $P_{\text{out}} = 2.42 \text{ hp}$

$P_{\text{loss}} = 267 \text{ W}$

$\eta = 87.1\%$

P16.20* (a) If V_T is doubled, the steady-state no-load speed is doubled.

(b) If the resistance is doubled, the steady-state no-load speed is not changed. (However, it will take longer for the motor to achieve this speed.)

(c) If B is doubled, the steady-state no-load speed is halved.

P16.23* $f_{\text{starting}} = 48.75\ \text{N}$

$u = 5.13\ \text{m/s}$

P16.27* Using the right-hand rule we see that in Figure 16.10, the north pole of the rotor is at the top of the rotor. Because the north rotor pole is attracted to the south stator pole, the torque is counterclockwise, as indicated in the figure.

In Figure 16.11, the north rotor poles are in the upper right-hand and lower left-hand portions of the rotor. South poles appear in the upper left-hand and lower right-hand parts of the rotor. Because the north rotor poles are attracted to the south stator poles, the torque is counterclockwise, as indicated in the figure.

P16.30* $T_{\text{dev}} = 19.10\ \text{Nm}$ $\quad P_{\text{dev}} = 2400\ \text{W}$ $\quad V_T = 253\ \text{V}$

P16.33* $N \cong 64$

P16.36* $n_2 = 1600\ \text{rpm}$

P16.39* (a) $P_{\text{dev}} = 44.26\ \text{kW} = 59.33\ \text{hp}$

$P_{R_A} = 1.061\ \text{kW}$

$P_{\text{rot}} = 6.96\ \text{kW} = 9.330\ \text{hp}$

(b) $n_m = 1530\ \text{rpm}$

P16.42* (a) The field current is

$$I_F = \frac{V_T}{R_F + R_{\text{adj}}} = \frac{240}{240} = 1.0\ \text{A}$$

From the magnetization curve shown in Figure P16.35, we find that $E_A = 165\ \text{V}$ with $I_F = 1.0\ \text{A}$ and $n_m = 1000\ \text{rpm}$. Neglecting losses at no load, we have $I_A = 0$ and $E_A = V_T = 240\ \text{V}$. Since E_A is proportional to speed, the no-load speed is:

$$n_{\text{no-load}} = \frac{240}{165} \times 1000\ \text{rpm} = 1455\ \text{rpm}$$

(b) $I_A = 9.6\ \text{A}$

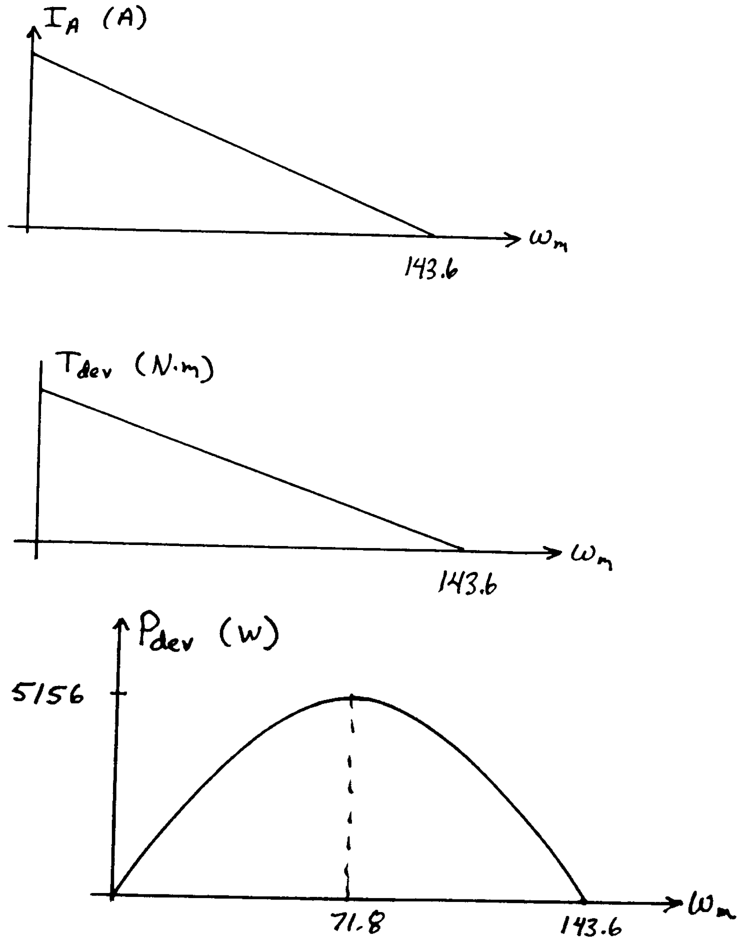
$T_{\text{load}} = 15.13\ \text{Nm}$

$P_F = 240\text{ W}$

$P_{R_A} = 138.2\text{ W}$

P16.45* (a) $n_{m,\text{ no-load}} = 1369\text{ rpm}$

(b)



P16.48* $\omega_{m1} = 174.3$ and $I_{A1} = 21.4\text{ A}$ for which $\eta = 87.2\%$

$\omega_{m2} = 25.67$ and $I_{A2} = 141\text{ A}$ for which $\eta = 13.5\%$

The first solution is more likely to fall within the rating because the efficiency for the second solution is very low.

P16.51* The magnetization curve is a plot of E_A versus the field current I_F at a stated speed. Because a permanent magnet motor does not have field current, the concept of a magnetization curve does not apply to it.

P16.54* $P_{\text{out}} = 30.87 \text{ W}$
$\eta = 74.83\%$

P16.57* $n_m = 1910 \text{ rpm}$

P16.65* See Figures 16.26, 16.27 and 16.28 in the book.

P16.68* $V_T = 33.33 \text{ V}$
$\frac{T_{\text{on}}}{T} = 0.667$

P16.71* $R_{added} = 0.379\ \Omega$

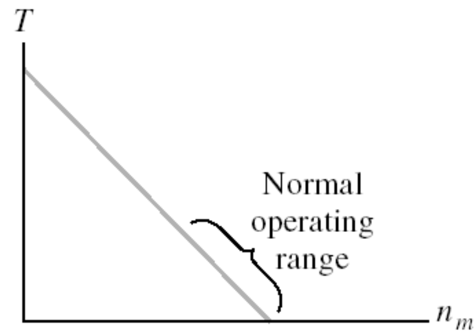
P16.77* $\text{voltage regulation} = 6.667\%$ $\quad R_L = 7.5\,\Omega \quad R_A = 0.5\,\Omega$
$T_{dev} = 19.10\ \text{Nm}$

P16.78* $I_L = 15\ A \quad V_L = 112.5\ \text{V} \quad P_{\text{dev}} = 1800\ \text{W}$

Practice Test

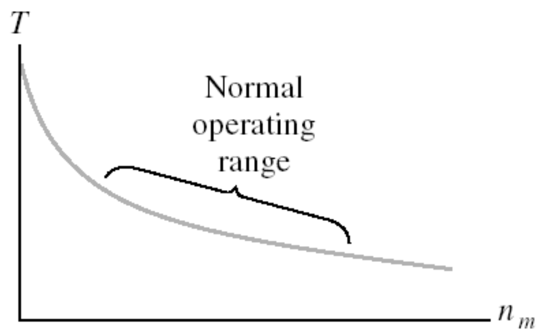
T16.1 The windings are the field winding, which is on the stator, and the armature winding, which is on the rotor. The armature current varies with mechanical load.

T16.2 See Figure 16.5(c) in the book. The speed becomes very high, and the machine can be destroyed.



(c) Shunt-connected or permanent-magnet dc motor

T16.3 See Figure 16.5(d) in the book.



(d) Series-connected dc motor or universal motor

T16.4 $$\text{speed regulation} = \frac{n_{\text{no-load}} - n_{\text{full-load}}}{n_{\text{full-load}}} \times 100\%$$

T16.5 To obtain the magnetization curve, we drive the machine at constant speed and plot the open-circuit armature voltage E_A versus field current I_F.

T16.6 Power losses in a shunt-connected dc motor are 1. Field loss, which is the power consumed in the resistances of the field circuit. 2. Armature loss, which is the power converted to heat in the armature resistance. 3. Rotational losses, which include friction, windage, eddy-current loss, and hysteresis loss.

T16.7 A universal motor is an ac motor that similar in construction to a series-connected dc motor. In principle, it can be operated from either ac or dc sources. The stator of a universal motor is usually laminated to reduce eddy-current loss. Compared to other single-phase ac motors, the universal motor has a higher power to weight ratio, produces a larger starting torque without excessive current, slows down under heavy loads so the power is more nearly constant, and can be designed to operate at higher speeds. A disadvantage of the universal motor is that it contains brushes and a commutator resulting in shorter service life.

T16.8 1. Vary the voltage supplied to the armature circuit while holding the field constant.

2. Vary the field current while holding the armature supply voltage constant.

3. Insert resistance in series with the armature circuit.

T16.9 Equation 16.15 states

$$E_A = K\varphi\omega_m$$

With constant field current, the magnetic flux φ is constant. Therefore, the back emf E_A is proportional to machine speed ω_m (or equivalently to n_m). Thus, we have

n_m(rpm)	E_A(V)
500	80
1500	240
2000	320

T16.10 Converting the speeds from rpm to radians/s, we have:

$$\omega_{m1} = n_{m1} \times \frac{2\pi}{60} = 1200 \times \frac{2\pi}{60} = 40\pi$$

$$\omega_{m2} = n_{m2} \times \frac{2\pi}{60} = 900 \times \frac{2\pi}{60} = 30\pi$$

Next, we can find the machine constant:

$$K\phi = \frac{E_A}{\omega_{m1}} = \frac{120}{40\pi} = \frac{3}{\pi} = 0.9549$$

The developed torque is:

$$T_{\text{dev}} = \frac{P_{\text{dev}}}{\omega_{m2}} = \frac{4 \times 746}{30\pi} = 31.66\ \text{Nm}$$

Finally, the armature current is:

$$I_A = \frac{T_{\text{dev}}}{K\phi} = \frac{31.66}{0.9549} = 33.16\ A$$

T16.11 (a) $E_A = V_T - R_A I_A = 230\text{ V}$

$$K\varphi = \frac{E_A}{\omega_m} = \frac{230}{1200(2\pi/60)} = 1.830$$

$$P_{\text{in}} = V_T I_A = 4800\text{ W}$$

$$P_{\text{out}} = 6 \times 746 = 4476\text{ W}$$

$$P_{R_A} = R_A I_A^2 = 200\text{ W}$$

$$P_{\text{rot}} = P_{\text{in}} - P_{\text{out}} - P_{R_A} = 124\text{ W}$$

$$P_{\text{dev}} = P_{\text{out}} + P_{\text{rot}} = 4600\text{ W}$$

$$T_{\text{dev}} = \frac{P_{\text{dev}}}{\omega_{\text{m}}} = \frac{4600}{1200 \times \frac{2\pi}{60}} = 36.60\text{ Nm}$$

(b) $$T_{\text{rot}} = \frac{P_{\text{rot}}}{\omega_m} = \frac{124}{1200 \times \frac{2\pi}{60}} = 0.9868\text{ Nm}$$

$$I_{A,\text{ no-load}} = \frac{T_{\text{rot}}}{K\phi} = 0.5392\ A$$

$$E_{A,\text{ no-load}} = V_T - R_A I_A = 239.73\quad\text{V}$$

$$\omega_{m,\text{ no-load}} = \frac{E_{A,\text{ no-load}}}{K\phi} = 131.0\ \text{rad/s}$$

$$n_{m,\text{ no-load}} = 1251\quad\text{rpm}$$

$$\text{speed regulation} = \frac{n_{\text{no-load}} - n_{\text{full-load}}}{n_{\text{full-load}}} \times 100\% = 4.25\%$$

T16.12 For $I_A = 20\ A$, we have:

$$\omega_{\text{m}} = n_m \times \frac{2\pi}{60} = 1000 \times \frac{2\pi}{60} = 104.7\ \text{radian/s}$$

$$E_A = V_T - (R_F + R_A)I_A = 226\text{ V}$$

Rearranging Equation 16.30 and substituting values, we have:

$$KK_F = \frac{E_A}{I_A \omega_m} = \frac{226}{20 \times 104.7} = 0.1079$$

For $I_A = 10\ A$, we have:

$$E_A = V_T - (R_F + R_A)I_A = 233\text{ V}$$

$$\omega_{\text{m}} = \frac{E_A}{KK_F I_A} = \frac{233}{0.1079 \times 10} = 215.9\ \text{radian/s}$$

$$n_m = 2062\text{ rpm}$$