6–24. An induction motor is running at the rated conditions. If the shaft load is now increased, how do the following quantities change?

(a) Mechanical speed
(b) Slip
(c) Rotor induced voltage
(d) Rotor current
(e) Rotor frequency
(f) P_{RCL}
(g) Synchronous speed

PROBLEMS

6–1. A 220-V, three-phase, six-pole, 50-Hz induction motor is running at a slip of 3.5 percent. Find:

(a) The speed of the magnetic fields in revolutions per minute
(b) The speed of the rotor in revolutions per minute
(c) The slip speed of the rotor
(d) The rotor frequency in hertz

6–2. Answer the questions in Problem 6–1 for a 480-V, three-phase, two-pole, 60-Hz induction motor running at a slip of 0.025.

6–3. A three-phase, 60-Hz induction motor runs at 715 r/min at no load and at 670 r/min at full load.

(a) How many poles does this motor have?
(b) What is the slip at rated load?
(c) What is the speed at one-quarter of the rated load?
(d) What is the rotor's electrical frequency at one-quarter of the rated load?

6–4. A 50-kW, 460-V, 50-Hz, two-pole induction motor has a slip of 5 percent when operating at full-load conditions. At full-load conditions, the friction and windage losses are 700 W, and the core losses are 600 W. Find the following values for full-load conditions:

(a) The shaft speed n_m
(b) The output power in watts
(c) The load torque τ_{load} in newton-meters
(d) The induced torque τ_{ind} in newton-meters
(e) The rotor frequency in hertz

6–5. A 208-V, four-pole, 60-Hz, Y-connected wound-rotor induction motor is rated at 30 hp. Its equivalent circuit components are

$$R_1 = 0.100\ \Omega \qquad R_2 = 0.070\ \Omega \qquad X_M = 10.0\ \Omega$$
$$X_1 = 0.210\ \Omega \qquad X_2 = 0.210\ \Omega$$
$$P_{mech} = 500\ \text{W} \qquad P_{misc} \approx 0 \qquad P_{core} = 400\ \text{W}$$

For a slip of 0.05, find

(a) The line current I_L
(b) The stator copper losses P_{SCL}
(c) The air-gap power P_{AG}
(d) The power converted from electrical to mechanical form P_{conv}
(e) The induced torque τ_{ind}
(f) The load torque τ_{load}

(g) The overall machine efficiency η

(h) The motor speed in revolutions per minute and radians per second

6–6. For the motor in Problem 6–5, what is the slip at the pullout torque? What is the pullout torque of this motor?

6–7. (a) Calculate and plot the torque–speed characteristic of the motor in Problem 6–5.

(b) Calculate and plot the output-power-versus-speed curve of the motor in Problem 6–5.

6–8. For the motor of Problem 6–5, how much additional resistance (referred to the stator circuit) would it be necessary to add to the rotor circuit to make the maximum torque occur at starting conditions (when the shaft is not moving)? Plot the torque–speed characteristic of this motor with the additional resistance inserted.

6–9. If the motor in Problem 6–5 is to be operated on a 50-Hz power system, what must be done to its supply voltage? Why? What will the equivalent circuit component values be at 50 Hz? Answer the questions in Problem 6–5 for operation at 50 Hz with a slip of 0.05 and the proper voltage for this machine.

6–10. A three-phase, 60-Hz, two-pole induction motor runs at a no-load speed of 3580 r/min and a full-load speed of 3440 r/min. Calculate the slip and the electrical frequency of the rotor at no-load and full-load conditions. What is the speed regulation of this motor [Equation (3-68)]?

6–11. The input power to the rotor circuit of a six-pole, 60-Hz induction motor running at 1100 r/min is 5 kW. What is the rotor copper loss in this motor?

6–12. The power crossing the air gap of a 60-Hz, four-pole induction motor is 25 kW, and the power converted from electrical to mechanical form in the motor is 23.2 kW.

(a) What is the slip of the motor at this time?

(b) What is the induced torque in this motor?

(c) Assuming that the mechanical losses are 300 W at this slip, what is the load torque of this motor?

6–13. Figure 6–18a shows a simple circuit consisting of a voltage source, a resistor, and two reactances. Find the Thevenin equivalent voltage and impedance of this circuit at the terminals. Then derive the expressions for the magnitude of $\mathbf{V}_{TH}$ and for R_{TH} given in Equations (6–41*b*) and (6–44).

6–14. Figure P6–1 shows a simple circuit consisting of a voltage source, two resistors, and two reactances in parallel with each other. If the resistor R_L is allowed to vary, but all the other components are constant, at what value of R_L will the maximum possible power be supplied to it? *Prove* your answer. (*Hint:* Derive an expression for load power in terms of V, R_S, X_S, R_L, and X_L and take the partial derivative of that expression with respect to R_L.) Use this result to derive the expression for the pullout torque [Equation (6–54)].

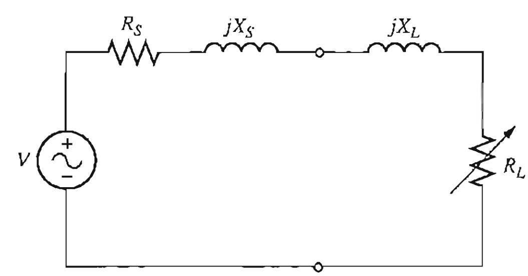

FIGURE P6–1
Circuit for Problem 6–14.

6–15. A 460-V, 60-Hz, four-pole, Y-connected induction motor is rated at 25 hp. The equivalent circuit parameters are

$R_1 = 0.15\ \Omega$	$R_2 = 0.154\ \Omega$	$X_M = 20\ \Omega$
$X_1 = 0.852\ \Omega$	$X_2 = 1.066\ \Omega$	
$P_{F\&W} = 400$ W	$P_{misc} = 150$ W	$P_{core} = 400$ W

For a slip of 0.02, find
(*a*) The line current I_L
(*b*) The stator power factor
(*c*) The rotor power factor
(*d*) The rotor frequency
(*e*) The stator copper losses P_{SCL}
(*f*) The air-gap power P_{AG}
(*g*) The power converted from electrical to mechanical form P_{conv}
(*h*) The induced torque τ_{ind}
(*i*) The load torque τ_{load}
(*j*) The overall machine efficiency η
(*k*) The motor speed in revolutions per minute and radians per second
(*l*) What is the starting code letter for this motor?

6–16. For the motor in Problem 6–15, what is the pullout torque? What is the slip at the pullout torque? What is the rotor speed at the pullout torque?

6–17. If the motor in Problem 6–15 is to be driven from a 460-V, 50-Hz power supply, what will the pullout torque be? What will the slip be at pullout?

6–18. Plot the following quantities for the motor in Problem 6–15 as slip varies from 0 percent to 10 percent: (*a*) τ_{ind} (*b*) P_{conv} (*c*) P_{out} (*d*) efficiency η. At what slip does P_{out} equal the rated power of the machine?

6–19. A dc test is performed on a 460-V, Δ-connected, 100-hp induction motor. If $V_{DC} =$ 21 V and $I_{DC} = 72$ A, what is the stator resistance R_1? *Why is this so?*

6–20. A 208-V, six-pole, Y-connected, 25-hp design class B induction motor is tested in the laboratory, with the following results:

No load:	208 V, 24.0 A, 1400 W, 60 Hz
Locked rotor:	24.6 V, 64.5 A, 2200 W, 15 Hz
dc test:	13.5 V, 64 A

Find the equivalent circuit of this motor, and plot its torque–speed characteristic curve.

6–21. A 460-V, 10-hp, four-pole, Y-connected, insulation class F, service factor 1.15 induction motor has the following parameters

$R_1 = 0.54\ \Omega$	$R_2 = 0.488\ \Omega$	$X_M = 51.12\ \Omega$
$X_1 = 2.093\ \Omega$	$X_2 = 3.209\ \Omega$	
$P_{F\&W} = 150$ W	$P_{misc} = 50$ W	$P_{core} = 150$ kW

For a slip of 0.02, find
(*a*) The line current I_L
(*b*) The stator power factor

(c) The rotor power factor
(d) The rotor frequency
(e) The stator copper losses P_{SCL}
(f) The air-gap power P_{AG}
(g) The power converted from electrical to mechanical form P_{conv}
(h) The induced torque τ_{ind}
(i) The load torque τ_{load}
(j) The overall machine efficiency η
(k) The motor speed in revolutions per minute and radians per second
(l) Sketch the power flow diagram for this motor.
(m) What is the starting code letter for this motor?
(n) What is the maximum acceptable temperature rise in this motor, given its insulation class?
(o) What does the service factor of this motor mean?

6–22. Plot the torque–speed characteristic of the motor in Problem 6–21. What is the starting torque of this motor?

6–23. A 460-V, four-pole, 75-hp, 60-Hz, Y-connected, three-phase induction motor develops its full-load induced torque at 1.2 percent slip when operating at 60 Hz and 460 V. The per-phase circuit model impedances of the motor are

$$R_1 = 0.058\ \Omega \qquad X_M = 18\ \Omega$$
$$X_1 = 0.32\ \Omega \qquad X_2 = 0.386\ \Omega$$

Mechanical, core, and stray losses may be neglected in this problem.
(a) Find the value of the rotor resistance R_2.
(b) Find τ_{max}, s_{max}, and the rotor speed at maximum torque for this motor.
(c) Find the starting torque of this motor.
(d) What code letter factor should be assigned to this motor?

6–24. Answer the following questions about the motor in Problem 6–21.
(a) If this motor is started from a 460-V infinite bus, how much current will flow in the motor at starting?
(b) If transmission line with an impedance of $0.50 + j0.35\ \Omega$ per phase is used to connect the induction motor to the infinite bus, what will the starting current of the motor be? What will the motor's terminal voltage be on starting?
(c) If an ideal 1.4:1 step-down autotransformer is connected between the transmission line and the motor, what will the current be in the transmission line during starting? What will the voltage be at the motor end of the transmission line during starting?

6–25. In this chapter, we learned that a step-down autotransformer could be used to reduce the starting current drawn by an induction motor. While this technique works, an autotransformer is relatively expensive. A much less expensive way to reduce the starting current is to use a device called *Y–Δ starter* (described earlier in this chapter). If an induction motor is normally Δ-connected, it is possible to reduce its phase voltage V_ϕ (and hence its starting current) by simply reconnecting the stator windings in Y during starting, and then restoring the connections to Δ when the motor comes up to speed. Answer the following questions about this type of starter.
(a) How would the phase voltage at starting compare with the phase voltage under normal running conditions?
(b) How would the starting current of the Y-connected motor compare to the starting current if the motor remained in a Δ-connection during starting?

6–26. A 460-V, 50-hp, six-pole, Δ-connected, 60-Hz, three-phase induction motor has a full-load slip of 4 percent, an efficiency of 91 percent, and a power factor of 0.87 lagging. At startup, the motor develops 1.75 times the full-load torque but draws 7 times the rated current at the rated voltage. This motor is to be started with an autotransformer-reduced voltage starter.

(a) What should the output voltage of the starter circuit be to reduce the starting torque until it equals the rated torque of the motor?

(b) What will the motor starting current and the current drawn from the supply be at this voltage?

6–27. A wound-rotor induction motor is operating at rated voltage and frequency with its slip rings shorted and with a load of about 25 percent of the rated value for the machine. If the rotor resistance of this machine is doubled by inserting external resistors into the rotor circuit, explain what happens to the following:

(a) Slip s

(b) Motor speed n_m

(c) The induced voltage in the rotor

(d) The rotor current

(e) τ_{ind}

(f) P_{out}

(g) P_{RCL}

(h) Overall efficiency η

6–28. A 460-V, 75-hp, four-pole, Y-connected induction motor has the following parameters:

$$R_1 = 0.058\ \Omega \qquad R_2 = 0.037\ \Omega \qquad X_M = 9.24\ \Omega$$

$$X_1 = 0.320\ \Omega \qquad X_2 = 0.386\ \Omega$$

$$P_{F\&W} = 650\ \text{W} \qquad P_{misc} = 150\ \text{W} \qquad P_{core} = 600\ \text{kW}$$

For a slip of 0.01, find

(a) The line current I_L

(b) The stator power factor

(c) The rotor power factor

(d) The rotor frequency

(e) The stator copper losses P_{SCL}

(f) The air-gap power P_{AG}

(g) The power converted from electrical to mechanical form P_{conv}

(h) The induced torque τ_{ind}

(i) The load torque τ_{load}

(j) The overall machine efficiency η

(k) The motor speed in revolutions per minute and radians per second

(l) Sketch the power flow diagram for this motor.

(m) What is the starting code letter for this motor?

6–29. Plot the torque–speed characteristic of the motor in Problem 6–28. What is the starting torque of this motor?

6–30. Answer the following questions about a 460-V, Δ-connected, two-pole, 100-hp, 60-Hz, starting code letter F induction motor:

(a) What is the maximum starting current that this machine's controller must be designed to handle?

(b) If the controller is designed to switch the stator windings from a Δ-connection to a Y-connection during starting, what is the maximum starting current that the controller must be designed to handle?

(c) If a 1.25:1 step-down autotransformer starter is used during starting, what is the maximum starting current that it must be designed to handle?

6–31. When it is necessary to stop an induction motor very rapidly, many induction motor controllers reverse the direction of rotation of the magnetic fields by switching any two stator leads. When the direction of rotation of the magnetic fields is reversed, the motor develops an induced torque opposite to the current direction of rotation, so it quickly stops and tries to start turning in the opposite direction. If power is removed from the stator circuit at the moment when the rotor speed goes through zero, then the motor has been stopped very rapidly. This technique for rapidly stopping an induction motor is called *plugging*. The motor of Problem 6–23 is running at rated conditions and is to be stopped by plugging.

(a) What is the slip s before plugging?

(b) What is the frequency of the rotor before plugging?

(c) What is the induced torque τ_{ind} before plugging?

(d) What is the slip s immediately after switching the stator leads?

(e) What is the frequency of the rotor immediately after switching the stator leads?

(f) What is the induced torque τ_{ind} immediately after switching the stator leads?

6–32. A 460-V, 10-hp, two-pole, Y-connected induction motor has the following parameters:

$$R_1 = 0.54\ \Omega \qquad X_1 = 2.093\ \Omega \qquad X_M = 51.12\ \Omega$$

$$P_{F\&W} = 150\ \text{W} \qquad P_{misc} = 50\ \text{W} \qquad P_{core} = 150\ \text{kW}$$

The rotor is a dual-cage design, with a tightly coupled, high-resistance outer bar and a loosely coupled, low-resistance inner bar (see Figure 6–25c). The parameters of the outer bar are

$$R_2 = 3.20\ \Omega \qquad X_2 = 2.00\ \Omega$$

The resistance is high due to the lower cross-sectional area, and the reactance is relatively low due to the tight coupling between the rotor and stator. The parameters of the inner bar are

$$R_2 = 0.382\ \Omega \qquad X_2 = 5.10\ \Omega$$

The resistance is low due to the high cross-sectional area, but the reactance is relatively high due to the quite loose coupling between the rotor and stator.

Calculate the torque–speed characteristic for this induction motor, and compare it to the torque–speed characteristic for the single-cage design in Problem 6–21. How do the curves differ? Explain the differences.

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