If this value is exceeded, the rotor will not be able to stay locked in with the stator magnetic fields, and the motor will *slip poles.*

If the field current of a synchronous motor is varied while its shaft load remains constant, then the reactive power supplied or consumed by the motor will vary. If $E_A \cos \delta > V_\phi$, the motor will supply reactive power, while if $E_A \cos \delta < V_\phi$, the motor will consume reactive power.

A synchronous motor has no net starting torque and so cannot start by itself. There are three main ways to start a synchronous motor:

1. Reduce the stator frequency to a safe starting level.
2. Use an external prime mover.
3. Put amortisseur or damper windings on the motor to accelerate it to near-synchronous speed before a direct current is applied to the field windings.

   If damper windings are present on a motor, they will also increase the stability of the motor during load transients.

## QUESTIONS

6–1. What is the difference between a synchronous motor and a synchronous generator?
6–2. What is the speed regulation of a synchronous motor?
6–3. When would a synchronous motor be used even though its constant-speed characteristic was not needed?
6–4. Why can't a synchronous motor start by itself?
6–5. What techniques are available to start a synchronous motor?
6–6. What are amortisseur windings? Why is the torque produced by them unidirectional at starting, while the torque produced by the main field winding alternates direction?
6–7. What is a synchronous capacitor? Why would one be used?
6–8. Explain, using phasor diagrams, what happens to a synchronous motor as its field current is varied. Derive a synchronous motor V curve from the phasor diagram.
6–9. Is a synchronous motor's field circuit in more danger of overheating when it is operating at a leading or at a lagging power factor? Explain, using phasor diagrams.
6–10. A synchronous motor is operating at a fixed real load, and its field current is increased. If the armature current falls, was the motor initially operating at a lagging or a leading power factor?
6–11. Why must the voltage applied to a synchronous motor be derated for operation at frequencies lower than the rated value?

## PROBLEMS

6–1. A 480-V, 60 Hz four-pole synchronous motor draws 50 A from the line at unity power factor and full load. Assuming that the motor is lossless, answer the following questions:
   (a) What is the output torque of this motor? Express the answer both in newton-meters and in pound-feet.

(b) What must be done to change the power factor to 0.8 leading? Explain your answer, using phasor diagrams.

(c) What will the magnitude of the line current be if the power factor is adjusted to 0.8 leading?

6–2. A 480-V, 60 Hz 400-hp, 0.8-PF-leading, six-pole, Δ-connected synchronous motor has a synchronous reactance of 1.1 Ω and negligible armature resistance. Ignore its friction, windage, and core losses for the purposes of this problem.

(a) If this motor is initially supplying 400 hp at 0.8 PF lagging, what are the magnitudes and angles of $E_A$ and $I_A$?

(b) How much torque is this motor producing? What is the torque angle $\delta$? How near is this value to the maximum possible induced torque of the motor for this field current setting?

(c) If $|E_A|$ is increased by 15 percent, what is the new magnitude of the armature current? What is the motor's new power factor?

(d) Calculate and plot the motor's V curve for this load condition.

6–3. A 2300-V, 1000-hp, 0.8-PF leading, 60-Hz, two-pole, Y-connected synchronous motor has a synchronous reactance of 2.8 Ω and an armature resistance of 0.4 Ω. At 60 Hz, its friction and windage losses are 24 kW, and its core losses are 18 kW. The field circuit has a dc voltage of 200 V, and the maximum $I_F$ is 10 A. The open-circuit characteristic of this motor is shown in Figure P6–1. Answer the following questions about the motor, assuming that it is being supplied by an infinite bus.

(a) How much field current would be required to make this machine operate at unity power factor when supplying full load?

(b) What is the motor's efficiency at full load and unity power factor?

(c) If the field current were increased by 5 percent, what would the new value of the armature current be? What would the new power factor be? How much reactive power is being consumed or supplied by the motor?

(d) What is the maximum torque this machine is theoretically capable of supplying at unity power factor? At 0.8 PF leading?

6–4. Plot the V curves ($I_A$ versus $I_F$) for the synchronous motor of Problem 6–3 at no-load, half-load, and full-load conditions. (Note that an electronic version of the open-circuit characteristics in Figure P6–1 is available at the book's website. It may simplify the calculations required by this problem. Also, you may assume that $R_A$ is negligible for this calculation.)

6–5. If a 60-Hz synchronous motor is to be operated at 50 Hz, will its synchronous reactance be the same as at 60 Hz, or will it change? (Hint: Think about the derivation of $X_S$.)

6–6. A 480-V, 100-kW, 0.85-PF-leading, 50-Hz, six-pole, Y-connected synchronous motor has a synchronous reactance of 1.5 Ω and a negligible armature resistance. The rotational losses are also to be ignored. This motor is to be operated over a continuous range of speeds from 300 to 1000 r/min, where the speed changes are to be accomplished by controlling the system frequency with a solid-state drive.

(a) Over what range must the input frequency be varied to provide this speed control range?

(b) How large is $E_A$ at the motor's rated conditions?

(c) What is the maximum power that the motor can produce at rated speed with the $E_A$ calculated in part (b)?

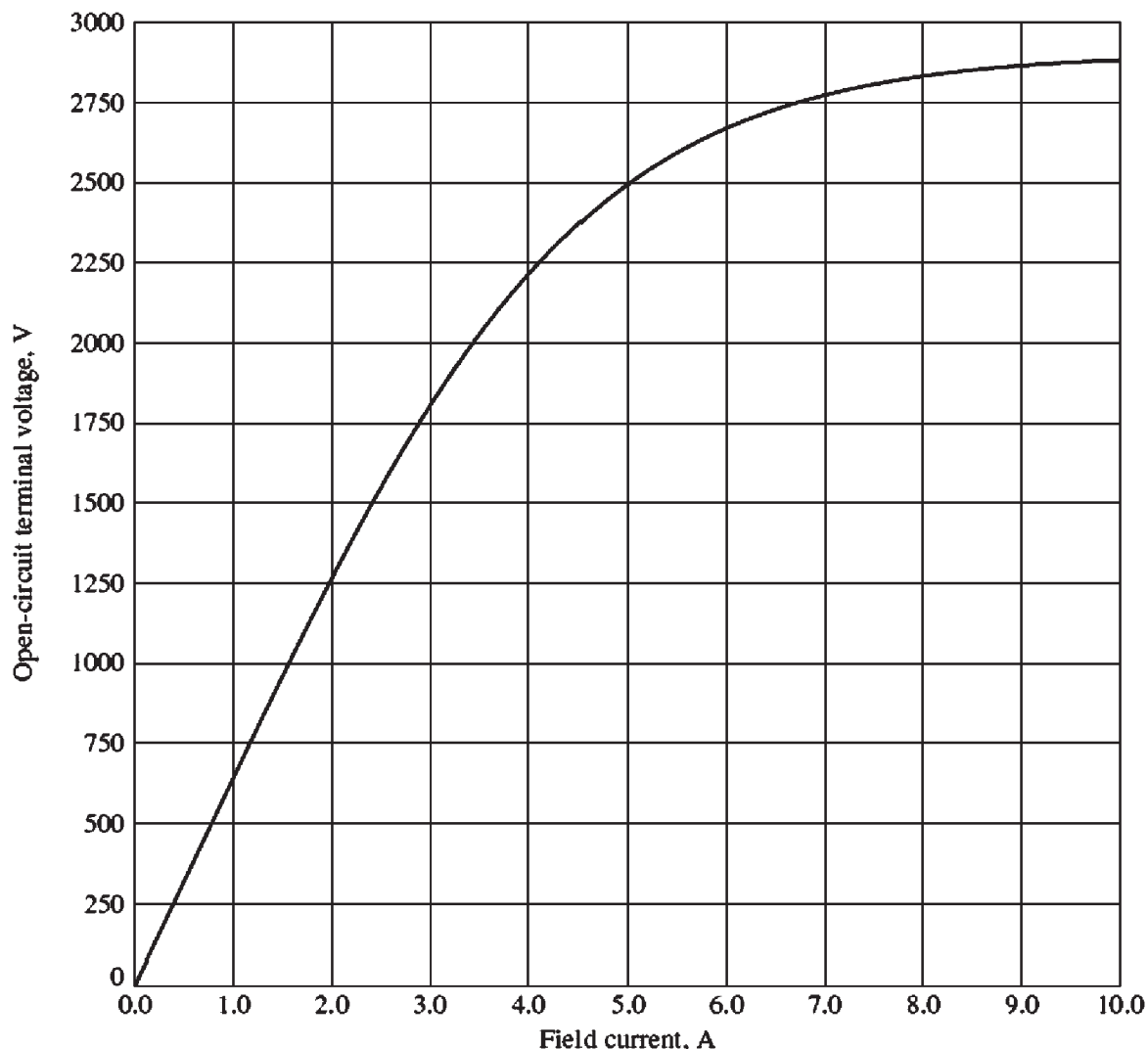(d) What is the largest $E_A$ could be at 300 r/min?

**FIGURE P6-1**

The open-circuit characteristic for the motor in Problems 6-3 and 6-4.

(e) Assuming that the applied voltage $V_\phi$ is derated by the same amount as $E_A$, what is the maximum power the motor could supply at 300 r/min?

(f) How does the power capability of a synchronous motor relate to its speed?

6-7. A 208-V, Y-connected synchronous motor is drawing 40 A at unity power factor from a 208-V power system. The field current flowing under these conditions is 2.7 A. Its synchronous reactance is 0.8 Ω. Assume a linear open-circuit characteristic.

(a) Find the torque angle δ.

(b) How much field current would be required to make the motor operate at 0.8 PF leading?

(c) What is the new torque angle in part b?

6-8. A synchronous machine has a synchronous reactance of 2.0 Ω per phase and an armature resistance of 0.4 Ω per phase. If $E_A$ = 460 ∠ –8° V and $V_\phi$ = 480 ∠ 0° V, is this machine a motor or a generator? How much power P is this machine consuming from or supplying to the electrical system? How much reactive power Q is this machine consuming from or supplying to the electrical system?

**6–9.** Figure P6–2 shows a synchronous motor phasor diagram for a motor operating at a leading power factor with no $R_A$. For this motor, the torque angle is given by

$$\tan \delta = \frac{X_S I_A \cos \theta}{V_\phi + X_S I_A \sin \theta}$$

$$\delta = \tan^{-1} \left( \frac{X_S I_A \cos \theta}{V_\phi + X_S I_A \sin \theta} \right)$$

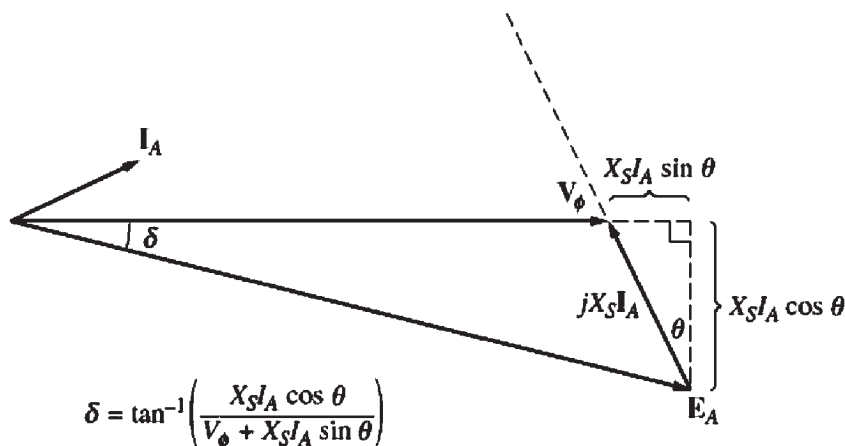Derive an equation for the torque angle of the synchronous motor *if the armature resistance is included.*



**FIGURE P6–2**
Phasor diagram of a motor at a leading power factor.

**6–10.** A 480-V, 375-kVA, 0.8-PF-lagging, Y-connected synchronous generator has a synchronous reactance of 0.4 $\Omega$ and a negligible armature resistance. This generator is supplying power to a 480-V, 80-kW, 0.8-PF-leading, Y-connected synchronous motor with a synchronous reactance of 1.1 $\Omega$ and a negligible armature resistance. The synchronous generator is adjusted to have a terminal voltage of 480 V when the motor is drawing the rated power at unity power factor.

   (*a*) Calculate the magnitudes and angles of $E_A$ for both machines.

   (*b*) If the flux of the motor is increased by 10 percent, what happens to the terminal voltage of the power system? What is its new value?

   (*c*) What is the power factor of the motor after the increase in motor flux?

**6–11.** A 480-V, 100-kW, 50-Hz, four-pole, Y-connected synchronous motor has a rated power factor of 0.85 leading. At full load, the efficiency is 91 percent. The armature resistance is 0.08 $\Omega$, and the synchronous reactance is 1.0 $\Omega$. Find the following quantities for this machine when it is operating at full load:

   (*a*) Output torque

   (*b*) Input power

   (*c*) $n_m$

   (*d*) $E_A$

   (*e*) $|I_A|$

   (*f*) $P_{conv}$

   (*g*) $P_{mech} + P_{core} + P_{stray}$

**6–12.** The Y-connected synchronous motor whose nameplate is shown in Figure 6–21 has a per-unit synchronous reactance of 0.9 and a per-unit resistance of 0.02.

(a) What is the rated input power of this motor?

(b) What is the magnitude of $E_A$ at rated conditions?

(c) If the input power of this motor is 10 MW, what is the maximum reactive power the motor can simultaneously supply? Is it the armature current or the field current that limits the reactive power output?

(d) How much power does the field circuit consume at the rated conditions?

(e) What is the efficiency of this motor at full load?

(f) What is the output torque of the motor at the rated conditions? Express the answer both in newton-meters and in pound-feet.

**6–13.** A 440-V, three-phase, Y-connected synchronous motor has a synchronous reactance of 1.5 Ω per phase. The field current has been adjusted so that the torque angle $\delta$ is 28° when the power supplied by the generator is 90 kW.

(a) What is the magnitude of the internal generated voltage $E_A$ in this machine?

(b) What are the magnitude and angle of the armature current in the machine? What is the motor's power factor?

(c) If the field current remains constant, what is the absolute maximum power this motor could supply?

**6–14.** A 460-V, 200-kVA, 0.80-PF-leading, 400-Hz, six-pole, Y-connected synchronous motor has negligible armature resistance and a synchronous reactance of 0.50 per unit. Ignore all losses.

(a) What is the speed of rotation of this motor?

(b) What is the output torque of this motor at the rated conditions?

(c) What is the internal generated voltage of this motor at the rated conditions?

(d) With the field current remaining at the value present in the motor in part c, what is the maximum possible output power from the machine?

**6–15.** A 100-hp, 440-V, 0.8-PF-leading, Δ-connected synchronous motor has an armature resistance of 0.22 Ω and a synchronous reactance of 3.0 Ω. Its efficiency at full load is 89 percent.

(a) What is the input power to the motor at rated conditions?

(b) What is the line current of the motor at rated conditions? What is the phase current of the motor at rated conditions?

(c) What is the reactive power consumed by or supplied by the motor at rated conditions?

(d) What is the internal generated voltage $E_A$ of this motor at rated conditions?

(e) What are the stator copper losses in the motor at rated conditions?

(f) What is $P_{conv}$ at rated conditions?

(g) If $E_A$ is decreased by 10 percent, how much reactive power will be consumed by or supplied by the motor?

**6–16.** Answer the following questions about the machine of Problem 6–15.

(a) If $E_A = 430 \angle 13.5°$ V and $V_\phi = 440 \angle 0°$ V, is this machine consuming real power from or supplying real power to the power system? Is it consuming reactive power from or supplying reactive power to the power system?

(b) Calculate the real power $P$ and reactive power $Q$ supplied or consumed by the machine under the conditions in part a. Is the machine operating within its ratings under these circumstances?

(c) If $E_A = 470 \angle -12°$ V and $V_\phi = 440 \angle 0°$ V, is this machine consuming real power from or supplying real power to the power system? Is it consuming reactive power from or supplying reactive power to the power system?

(d) Calculate the real power $P$ and reactive power $Q$ supplied or consumed by the machine under the conditions in part $c$. Is the machine operating within its ratings under these circumstances?

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