4–15. Explain in detail the concept behind capability curves.

4–16. What are short-time ratings? Why are they important in regular generator operation?

PROBLEMS

4–1. At a location in Europe, it is necessary to supply 1000 kW of 60-Hz power. The only power sources available operate at 50 Hz. It is decided to generate the power by means of a motor-generator set consisting of a synchronous motor driving a synchronous generator. How many poles should each of the two machines have in order to convert 50-Hz power to 60-Hz power?

4–2. A 13.8-kV, 50-MVA, 0.9-power-factor-lagging, 60-Hz, four-pole Y-connected synchronous generator has a synchronous reactance of 2.5 Ω and an armature resistance of 0.2 Ω. At 60 Hz, its friction and windage losses are 1 MW, and its core losses are 1.5 MW. The field circuit has a dc voltage of 120 V, and the maximum I_F is 10 A. The current of the field circuit is adjustable over the range from 0 to 10 A. The OCC of this generator is shown in Figure P4–1.

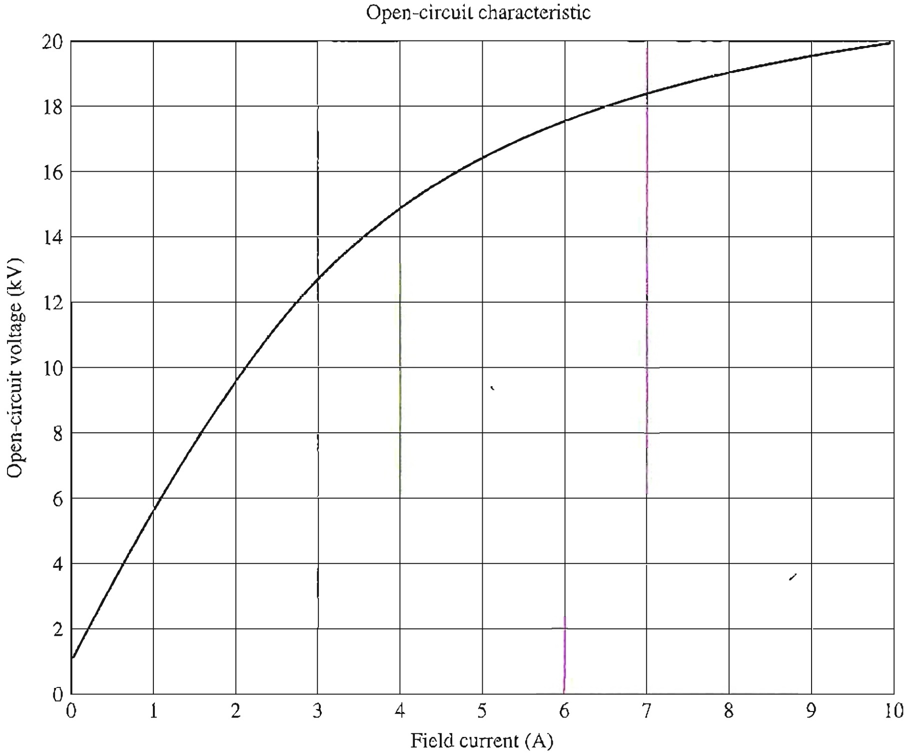

FIGURE P4–1
Open-circuit characteristic curve for the generator in Problem 4–2.

(*a*) How much field current is required to make the terminal voltage V_T (or line voltage V_L) equal to 13.8 kV when the generator is running at no load?

(*b*) What is the internal generated voltage E_A of this machine at rated conditions?

(c) What is the phase voltage V_ϕ of this generator at rated conditions?
(d) How much field current is required to make the terminal voltage V_T equal to 13.8 kV when the generator is running at rated conditions?
(e) Suppose that this generator is running at rated conditions, and then the load is removed without changing the field current. What would the terminal voltage of the generator be?
(f) How much steady-state power and torque must the generator's prime mover be capable of supplying to handle the rated conditions?
(g) Construct a capability curve for this generator.

4–3. Assume that the field current of the generator in Problem 4–2 has been adjusted to a value of 5 A.
(a) What will the terminal voltage of this generator be if it is connected to a Δ-connected load with an impedance of $24 \angle 25° \ \Omega$?
(b) Sketch the phasor diagram of this generator.
(c) What is the efficiency of the generator at these conditions?
(d) Now assume that another identical Δ-connected load is to be paralleled with the first one. What happens to the phasor diagram for the generator?
(e) What is the new terminal voltage after the load has been added?
(f) What must be done to restore the terminal voltage to its original value?

4–4. Assume that the field current of the generator in Problem 4–2 is adjusted to achieve rated voltage (13.8 kV) at full-load conditions in each of the following questions.
(a) What is the efficiency of the generator at rated load?
(b) What is the voltage regulation of the generator if it is loaded to rated kilovoltamperes with 0.9-PF-lagging loads?
(c) What is the voltage regulation of the generator if it is loaded to rated kilovoltamperes with 0.9-PF-leading loads?
(d) What is the voltage regulation of the generator if it is loaded to rated kilovoltamperes with unity-power-factor loads?
(e) Use MATLAB to plot the terminal voltage of the generator as a function of load for all three power factors.

4–5. Assume that the field current of the generator in Problem 4–2 has been adjusted so that it supplies rated voltage when loaded with rated current at unity power factor.
(a) What is the torque angle δ of the generator when supplying rated current at unity power factor?
(b) What is the maximum power that this generator can deliver to a unity power factor load when the field current is adjusted to the current value?
(c) When this generator is running at full load with unity power factor, how close is it to the static stability limit of the machine?

4–6. The internal generated voltage E_A of a Y-connected, three-phase synchronous generator is 14.4 kV, and the terminal voltage V_T is 12.8 kV. The synchronous reactance of this machine is 4 Ω, and the armature resistance can be ignored.
(a) If the torque angle of the generator $\delta = 18°$, how much power is being supplied by this generator at the current time?
(b) What is the power factor of the generator at this time?
(c) Sketch the phasor diagram under these circumstances.
(d) Ignoring losses in this generator, what torque must be applied to its shaft by the prime mover at these conditions?

4–7. A 100-MVA, 14.4-kV, 0.8-PF-lagging, 50-Hz, two-pole, Y-connected synchronous generator has a per-unit synchronous reactance of 1.1 and a per-unit armature resistance of 0.011.

(*a*) What are its synchronous reactance and armature resistance in ohms?

(*b*) What is the magnitude of the internal generated voltage E_A at the rated conditions? What is its torque angle δ at these conditions?

(*c*) Ignoring losses in this generator, what torque must be applied to its shaft by the prime mover at full load?

4–8. A 200-MVA, 12-kV, 0.85-PF-lagging, 50-Hz, 20-pole, Y-connected water turbine generator has a per-unit synchronous reactance of 0.9 and a per-unit armature resistance of 0.1. This generator is operating in parallel with a large power system (infinite bus).

(*a*) What is the speed of rotation of this generator's shaft?

(*b*) What is the magnitude of the internal generated voltage E_A at rated conditions?

(*c*) What is the torque angle of the generator at rated conditions?

(*d*) What are the values of the generator's synchronous reactance and armature resistance in ohms?

(*e*) If the field current is held constant, what is the maximum power possible out of this generator? How much reserve power or torque does this generator have at full load?

(*f*) At the absolute maximum power possible, how much reactive power will this generator be supplying or consuming? Sketch the corresponding phasor diagram. (Assume I_F is still unchanged.)

4–9. A 480-V, 250-kVA, 0.8-PF-lagging, two-pole, three-phase, 60-Hz synchronous generator's prime mover has a no-load speed of 3650 r/min and a full-load speed of 3570 r/min. It is operating in parallel with a 480-V, 250-kVA, 0.85-PF-lagging, four-pole, 60-Hz synchronous generator whose prime mover has a no-load speed of 1800 r/min and a full-load speed of 1780 r/min. The loads supplied by the two generators consist of 300 kW at 0.8 PF lagging.

(*a*) Calculate the speed droops of generator 1 and generator 2.

(*b*) Find the operating frequency of the power system.

(*c*) Find the power being supplied by each of the generators in this system.

(*d*) What must the generator's operators do to adjust the operating frequency to 60 Hz?

(*e*) If the current line voltage is 460 V, what must the generator's operators do to correct for the low terminal voltage?

4–10. Three physically identical synchronous generators are operating in parallel. They are all rated for a full load of 100 MW at 0.8 PF lagging. The no-load frequency of generator A is 61 Hz, and its speed droop is 3 percent. The no-load frequency of generator B is 61.5 Hz, and its speed droop is 3.4 percent. The no-load frequency of generator C is 60.5 Hz, and its speed droop is 2.6 percent.

(*a*) If a total load consisting of 230 MW is being supplied by this power system, what will the system frequency be, and how will the power be shared among the three generators?

(*b*) Create a plot showing the power supplied by each generator as a function of the total power supplied to all loads (you may use MATLAB to create this plot). At what load does one of the generators exceed its ratings? Which generator exceeds its ratings first?

(c) Is this power sharing in *(a)* acceptable? Why or why not?

(d) What actions could an operator take to improve the real power sharing among these generators?

4–11. A paper mill has installed three steam generators (boilers) to provide process steam and also to use some its waste products as an energy source. Since there is extra capacity, the mill has installed three 10-MW turbine generators to take advantage of the situation. Each generator is a 4160-V, 12.5 MVA, 60 Hz, 0.8-PF-lagging, two-pole, Y-connected synchronous generator with a synchronous reactance of 1.10 Ω and an armature resistance of 0.03 Ω. Generators 1 and 2 have a characteristic power–frequency slope s_P of 5 MW/Hz, and generators 3 has a slope of 6 MW/Hz.

(a) If the no-load frequency of each of the three generators is adjusted to 61 Hz, how much power will the three machines be supplying when the actual system frequency is 60 Hz?

(b) What is the maximum power the three generators can supply in this condition without the ratings of one of them being exceeded? At what frequency does this limit occur? How much power does each generator supply at that point?

(c) What would have to be done to get all three generators to supply their rated real and reactive powers at an overall operating frequency of 60 Hz?

(d) What would the internal generated voltages of the three generators be under this condition?

4–12. Suppose that you were an engineer planning a new electric co-generation facility for a plant with excess process steam. You have a choice of either two 10-MW turbine-generators or a single 20-MW turbine-generator. What would be the advantages and disadvantages of each choice?

4–13. A 25-MVA, 12.2-kV, 0.9-PF-lagging, three-phase, two-pole, Y-connected, 60-Hz synchronous generator was tested by the open-circuit test, and its air-gap voltage was extrapolated with the following results:

Open-circuit test					
Field current, A	320	365	380	475	570
Line voltage, kV	13.0	13.8	14.1	15.2	16.0
Extrapolated air-gap voltage, kV	15.4	17.5	18.3	22.8	27.4

The short-circuit test was then performed with the following results:

Short-circuit test					
Field current, A	320	365	380	475	570
Armature current, A	1040	1190	1240	1550	1885

The armature resistance is 0.6 Ω per phase.

(a) Find the unsaturated synchronous reactance of this generator in ohms per phase and ohms per unit.

(b) Find the approximate saturated synchronous reactance X_S at a field current of 380 A. Express the answer both in ohms per phase and per unit.

(c) Find the approximate saturated synchronous reactance at a field current of 475 A. Express the answer both in ohms per phase and in per unit.
(d) Find the short-circuit ratio for this generator.
(e) What is the internal generated voltage of this generator at rated conditions?
(f) What field current is required to achieve rated voltage at rated load?

4–14. During a short-circuit test, a Y-connected synchronous generator produces 100 A of short-circuit armature current per phase at a field current of 2.5 A. At the same field current, the open-circuit line voltage is measured to be 440 V.
(a) Calculate the saturated synchronous reactance under these conditions.
(b) If the armature resistance is 0.3 Ω per phase, and the generator supplies 60 A to a purely resistive Y-connected load of 3 Ω per phase at this field current setting, determine the voltage regulation under these load conditions.

4–15. A three-phase, Y-connected synchronous generator is rated 120 MVA, 13.8 kV, 0.8-PF-lagging, and 60 Hz. Its synchronous reactance is 1.2 Ω per phase, and its armature resistance is 0.1 Ω per phase.
(a) What is its voltage regulation?
(b) What would the voltage and apparent power rating of this generator be if it were operated at 50 Hz with the same armature and field losses as it had at 60 Hz?
(c) What would the voltage regulation of the generator be at 50 Hz?

Problems 4–16 to 4–26 refer to a six-pole, Y-connected synchronous generator rated at 1 MVA, 3.2 kV, 0.9 PF lagging, and 60 Hz. Its armature resistance R_A is 0.7 Ω. The core losses of this generator at rated conditions are 8 kW, and the friction and windage losses are 10 kW. The open-circuit and short-circuit characteristics are shown in Figure P4–2.

4–16. (a) What is the saturated synchronous reactance of this generator at the rated conditions?
(b) What is the unsaturated synchronous reactance of this generator?
(c) Plot the saturated synchronous reactance of this generator as a function of load.

4–17. (a) What are the rated current and internal generated voltage of this generator?
(b) What field current does this generator require to operate at the rated voltage, current, and power factor?

4–18. What is the voltage regulation of this generator at the rated current and power factor?

4–19. If this generator is operating at the rated conditions and the load is suddenly removed, what will the terminal voltage be?

4–20. What are the electrical losses in this generator at rated conditions?

4–21. If this machine is operating at rated conditions, what input torque must be applied to the shaft of this generator? Express your answer both in newton-meters and in pound-feet.

4–22. What is the torque angle δ of this generator at rated conditions?

4–23. Assume that the generator field current is adjusted to supply 3200 V under rated conditions. What is the static stability limit of this generator? (*Note:* You may ignore R_A to make this calculation easier.) How close is the full-load condition of this generator to the static stability limit?

4–24. Assume that the generator field current is adjusted to supply 3200 V under rated conditions. Plot the power supplied by the generator as a function of the torque angle δ.

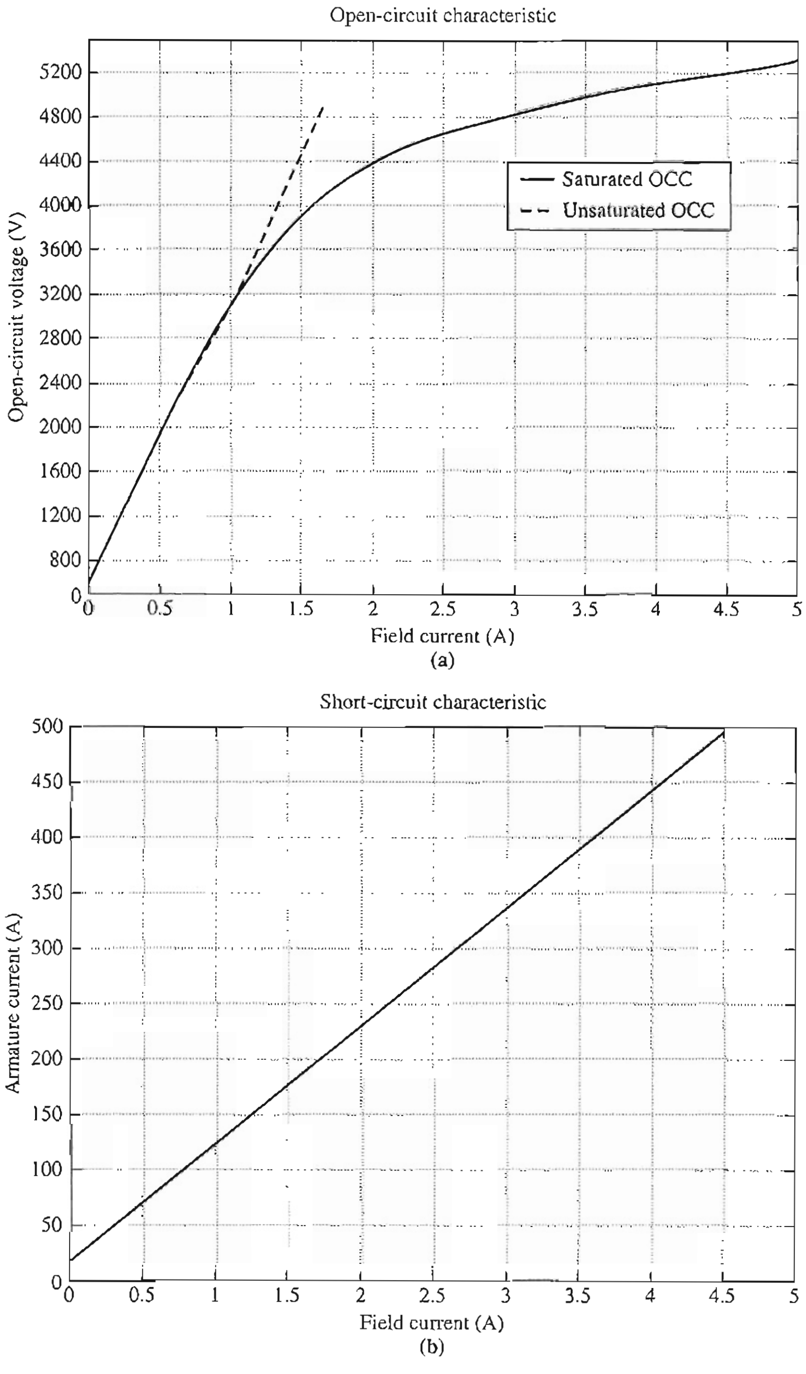

FIGURE P4–2
(a) Open-circuit characteristic curve for the generator in Problems 4–16 to 4–26. *(b)* Short-circuit characteristic curve for the generator in Problems 4–16 to 4–26.

4–25. Assume that the generator's field current is adjusted so that the generator supplies rated voltage at the rated load current and power factor. If the field current and the magnitude of the load current are held constant, how will the terminal voltage change as the load power factor varies from 0.9 PF lagging to 0.9 PF leading? Make a plot of the terminal voltage versus the load power factor.

4–26. Assume that the generator is connected to a 3200-V infinite bus, and that its field current has been adjusted so that it is supplying rated power and power factor to the bus. You may ignore the armature resistance R_A when answering the following questions.

(*a*) What will happen to the real and reactive power supplied by this generator if the field flux (and therefore E_A) is reduced by 5 percent?

(*b*) Plot the real power supplied by this generator as a function of the flux ϕ as the flux is varied from 80 percent to 100 percent of the flux at rated conditions.

(*c*) Plot the reactive power supplied by this generator as a function of the flux ϕ as the flux is varied from 80 percent to 100 percent of the flux at rated conditions.

(*d*) Plot the line current supplied by this generator as a function of the flux ϕ as the flux is varied from 80 percent to 100 percent of the flux at rated conditions.

4–27. Two identical 2.5-MVA, 1200-V 0.8-PF-lagging, 60-Hz, three-phase synchronous generators are connected in parallel to supply a load. The prime movers of the two generators happen to have different speed droop characteristics. When the field currents of the two generators are equal, one delivers 1200 A at 0.9 PF lagging, while the other delivers 900 A at 0.75 PF lagging.

(*a*) What are the real power and the reactive power supplied by each generator to the load?

(*b*) What is the overall power factor of the load?

(*c*) In what direction must the field current on each generator be adjusted in order for them to operate at the same power factor?

4–28. A generating station for a power system consists of four 300-MVA, 15-kV, 0.85-PF-lagging synchronous generators with identical speed droop characteristics operating in parallel. The governors on the generators' prime movers are adjusted to produce a 3-Hz drop from no load to full load. Three of these generators are each supplying a steady 200 MW at a frequency of 60 Hz, while the fourth generator (called the *swing generator*) handles all incremental load changes on the system while maintaining the system's frequency at 60 Hz.

(*a*) At a given instant, the total system loads are 650 MW at a frequency of 60 Hz. What are the no-load frequencies of each of the system's generators?

(*b*) If the system load rises to 725 MW and the generator's governor set points do not change, what will the new system frequency be?

(*c*) To what frequency must the no-load frequency of the swing generator be adjusted in order to restore the system frequency to 60 Hz?

(*d*) If the system is operating at the conditions described in part (*c*), what would happen if the swing generator were tripped off the line (disconnected from the power line)?

4–29. A 100-MVA, 14.4-kV, 0.8-PF-lagging, Y-connected synchronous generator has a negligible armature resistance and a synchronous reactance of 1.0 per unit. The generator is connected in parallel with a 60-Hz, 14.4-kV infinite bus that is capable of supplying or consuming any amount of real or reactive power with no change in frequency or terminal voltage.

(*a*) What is the synchronous reactance of the generator in ohms?

(*b*) What is the internal generated voltage $\mathbf{E}_A$ of this generator under rated conditions?

(c) What is the armature current $\mathbf{I}_A$ in this machine at rated conditions?

(d) Suppose that the generator is initially operating at rated conditions. If the internal generated voltage $\mathbf{E}_A$ is decreased by 5 percent, what will the new armature current $\mathbf{I}_A$ be?

(e) Repeat part (d) for 10, 15, 20, and 25 percent reductions in $\mathbf{E}_A$.

(f) Plot the magnitude of the armature current I_A as a function of E_A. (You may wish to use MATLAB to create this plot.)

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