SECTION 7.4

7.11 The inverse of the bus-admittance matrix is called a _____ matrix.

7.12 For a power system, modeled by its positive-sequence network, both bus-admittance matrix and bus-impedance matrix are symmetric.
(a) True (b) False

7.13 The bus-impedance equivalent circuit can be represented in the form of a "rake" with the diagonal elements, which are _____, and the non-diagonal (off-diagonal) elements, which are _____.

SECTION 7.5

7.14 A circuit breaker is designed to extinguish the arc by _____.

7.15 Power-circuit breakers are intended for service in the ac circuit above _____ V.

7.16 In circuit breakers, besides air or vacuum, what gaseous medium, in which the arc is elongated, is used?

7.17 Oil can be used as a medium to extinguish the arc in circuit breakers.
(a) True (b) False

7.18 Besides a blast of air/gas, the arc in a circuit breaker can be elongated by _____.

7.19 For distribution systems, standard reclosers are equipped for two or more reclosures, whereas multiple-shot reclosing in EHV systems is not a standard practice.
(a) True (b) False

7.20 Breakers of the 115 kV class and higher have a voltage range factor K = _____, such that their symmetrical interrupting current capability remains constant.

7.21 A typical fusible link metal in fuses is _____, and a typical filler material is _____.

7.22 The melting and clearing time of a current-limiting fuse is usually specified by a _____ curve.

PROBLEMS

SECTION 7.1

7.1 In the circuit of Figure 7.1, V = 277 volts, L = 2 mH, R = 0.4 Ω, and $\omega = 2\pi 60$ rad/s. Determine (a) the rms symmetrical fault current; (b) the rms asymmetrical fault current at the instant the switch closes, assuming maximum dc offset; (c) the rms asymmetrical fault current five cycles after the switch closes, assuming maximum dc offset; and (d) the dc offset as a function of time if the switch closes when the instantaneous source voltage is 300 volts.

7.2 Repeat Example 7.1 with V = 4 kV, X = 2 Ω, and R = 1 Ω

7.3 In the circuit of Figure 7.1, let R = 0.125 Ω., L = 10 mH, and the source voltage is $e(t) = 151 \sin(377t + \alpha)$ V. Determine the current response after closing the switch for the following cases: (a) no dc offset or (b) maximum dc offset. Sketch the current waveform up to t = 0.10 s corresponding to parts (a) and (b).

7.4 Consider the expression for $i(t)$ given by

$$i(t) = \sqrt{2}I_{rms}[\sin(\omega t - \theta_z) + \sin \theta_z . e^{-(\omega R/X)t}]$$

where $\theta_z = \tan^{-1}(\omega L/R)$.

(a) For (X/R) equal to zero and infinity, plot $i(t)$ as a function of (ωt).

(b) Comment on the dc offset of the fault current waveforms.

(c) Find the asymmetrical current factor and the time of peak, t_p, in milliseconds, for (X/R) ratios of zero and infinity.

7.5 If the source impedance at a 13.2-kV distribution substation bus is (0.5 + j1.5) Ω per phase, compute the rms and maximum peak instantaneous value of the fault current for a balanced three-phase fault. For the system (X/R) ratio of 3.0, the asymmetrical factor is 1.9495 and the time of peak is 7.1 ms (see Problem 7.4). Comment on the withstanding peak current capability to which all substation electrical equipment need to be designed.

SECTION 7.2

7.6 A 1000-MVA, 20-kV, 60-Hz, three-phase generator is connected through a 1000-MVA, 20-kV, Δ/345-kV, Y transformer to a 345-kV circuit breaker and a 345-kV transmission line. The generator reactances are $X_d'' = 0.17$, $X_d' = 0.30$, and $X_d = 1.5$ per unit, and its time constants are $T_d'' = 0.05$, $T_d' = 1.0$, and $T_A = 0.10$ s. The transformer series reactance is 0.10 per unit; transformer losses and exciting current are neglected. A three-phase short-circuit occurs on the line side of the circuit breaker when the generator is operated at rated terminal voltage and at no-load. The breaker interrupts the fault three cycles after fault inception. Determine (a) the subtransient current through the breaker in per-unit and in kA rms and (b) the rms asymmetrical fault current the breaker interrupts, assuming maximum dc offset. Neglect the effect of the transformer on the time constants.

7.7 For Problem 7.6, determine (a) the instantaneous symmetrical fault current in kA in phase a of the generator as a function of time, assuming maximum dc offset occurs in this generator phase, and (b) the maximum dc offset current in kA as a function of time that can occur in any one generator phase.

7.8 A 300-MVA, 13.8-kV, three-phase, 60-Hz, Y-connected synchronous generator is adjusted to produce rated voltage on open circuit. A balanced three-phase fault is applied to the terminals at t = 0. After analyzing the raw data, the symmetrical transient current is obtained as

$$i_{ac}(t) = 10^4(1 + e^{-t/\tau_1} + 6e^{-t/\tau_2}) \quad \text{A}$$

where $\tau_1 = 200$ ms and $\tau_2 = 15$ ms. (a) Sketch $i_{ac}(t)$ as a function of time for $0 \le t \le 500$ ms. (b) Determine X_d'' and X_d in per unit based on the machine ratings.

7.9 Two identical synchronous machines, each rated 60 MVA and 15 kV with a subtransient reactance of 0.1 p.u., are connected through a line of reactance 0.1 p.u. on the base of the machine rating. One machine is acting as a synchronous generator, while the other is working as a motor drawing 40 MW at 0.8 p.f. leading with a terminal voltage of 14.5 kV, when a symmetrical three-phase fault occurs at the motor terminals. Determine the subtransient currents in the generator, the motor, and the fault by using the internal voltages of the machines. Choose a base of 60 MVA and 15 kV in the generator circuit.

SECTION 7.3

7.10 Recalculate the subtransient current through the breaker in Problem 7.6 if the generator is initially delivering rated MVA at 0.80 p.f. lagging and at rated terminal voltage.

7.11 Solve Example 7.3 parts (a) and (c) without using the superposition principle. First calculate the internal machine voltages E_g'' and E_m'' using the prefault load current. Then determine the subtransient fault, generator, and motor currents directly from Figure 7.4(a). Compare your answers with those of Example 7.3.

7.12 Equipment ratings for the four-bus power system shown in Figure 7.14 are as follows:

Generator Gl:	500 MVA, 13.8 kV, X″ = 0.20 per unit
Generator G2:	750 MVA, 18 kV, X″ = 0.18 per unit
Generator G3:	1000 MVA, 20 kV, X″ = 0.17 per unit
Transformer Tl:	500 MVA, 13.8 Δ/500 Y kV, X = 0.12 per unit
Transformer T2:	750 MVA, 18 Δ/500 Y kV, X = 0.10 per unit
Transformer T3:	1000 MVA, 20 Δ/500 Y kV, X = 0.10 per unit
Each 500 kV line:	$X_1 = 50\ \Omega$.

A three-phase short circuit occurs at bus 1, where the prefault voltage is 525 kV. Prefault load current is neglected. Draw the positive-sequence reactance diagram in per unit on a 1000-MVA, 20-kV base in the zone of generator G3. Determine (a) the Thévenin reactance in per unit at the fault, (b) the subtransient fault current in per unit and in kA rms, and (c) contributions to the fault current from generator Gl and from line 1–2.

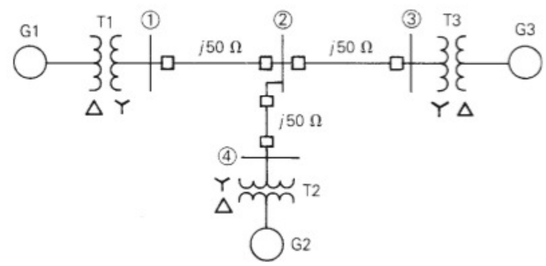


FIGURE 7.14 Problems 7.12, 7.13, 7.19, 7.24, 7.25, and 7.26

7.13 For the power system given in Problem 7.12, a three-phase short circuit occurs at bus 2, where the prefault voltage is 525 kV. Prefault load current is neglected. Determine the (a) Thévenin equivalent at the fault, (b) subtransient fault current in per unit and in kA rms, and (c) contributions to the fault from lines 1–2, 2–3, and 2–4.

7.14 Equipment ratings for the five-bus power system shown in Figure 7.15 are as follows:

Generator Gl:	50 MVA, 12 kV, $X'' = 0.2$ per unit
Generator G2:	100 MVA, 15 kV, $X'' = 0.2$ per unit
Transformer Tl:	50 MVA, 10 kV Y/138 kV Y, $X = 0.10$ per unit
Transformer T2:	100 MVA, 15 kV Δ/138 kV Y, $X = 0.10$ per unit
Each 138-kV line:	$X_1 = 40\ \Omega$.

A three-phase short circuit occurs at bus 5, where the prefault voltage is 15 kV. Prefault load current is neglected. (a) Draw the positive-sequence reactance diagram in per unit on a 100-MVA, 15-kV base in the zone of generator G2. Determine (b) the Thévenin equivalent at the fault, (c) the subtransient fault current in per unit and in kA rms, and (d) contributions to the fault from generator G2 and from transformer T2.

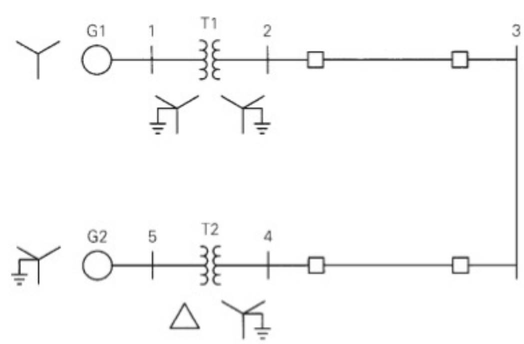
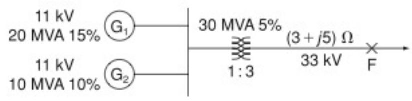


FIGURE 7.15 Problems 7.14, 7.15, 7.20

7.15 For the power system given in Problem 7.14, a three-phase short circuit occurs at bus 4, where the prefault voltage is 138 kV. Prefault load current is neglected. Determine (a) the Thévenin equivalent at the fault, (b) the subtransient fault current in per unit and in kA rms, and (c) contributions to the fault from transformer T2 and from line 3–4.

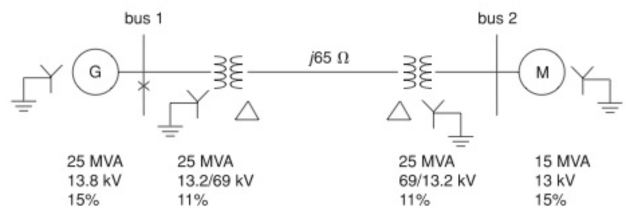
7.16 In the system shown in Figure 7.16, a three-phase short circuit occurs at point F. Assume that prefault currents are zero and that the generators are operating at rated voltage. Determine the fault current.

FIGURE 7.16
Problem 7.16



7.17 A three-phase short circuit occurs at the generator bus (bus 1) for the system shown in Figure 7.17. Neglecting prefault currents and assuming that the generator is operating at its rated voltage, determine the subtransient fault current using superposition.

FIGURE 7.17
Problem 7.17



SECTION 7.4

7.18 (a) The bus impedance matrix for a three-bus power system is

$$\boldsymbol{Z}_{\text{bus}} = j\begin{bmatrix} 0.12 & 0.08 & 0.04 \\ 0.08 & 0.12 & 0.06 \\ 0.04 & 0.06 & 0.08 \end{bmatrix} \quad \text{per unit}$$

where subtransient reactances were used to compute $\boldsymbol{Z}_{\text{bus}}$. Prefault voltage is 1.0 per unit and prefault current is neglected. (a) Draw the bus impedance matrix equivalent circuit (rake equivalent). Identify the per-unit self- and mutual impedances as well as the prefault voltage in the circuit. (b) A three-phase short circuit occurs at bus 2. Determine the subtransient fault current and the voltages at buses 1, 2, and 3 during the fault.

(c) Repeat for the case of

$$\boldsymbol{Z}_{\text{bus}} = j\begin{bmatrix} 0.4 & 0.1 & 0.3 \\ 0.1 & 0.8 & 0.5 \\ 0.3 & 0.5 & 1.2 \end{bmatrix} \quad \text{per unit}$$

7.19 Determine $\boldsymbol{Y}_{\text{bus}}$ in per unit for the circuit in Problem 7.12. Then invert $\boldsymbol{Y}_{\text{bus}}$ to obtain $\boldsymbol{Z}_{\text{bus}}$.

7.20 Determine $\boldsymbol{Y}_{\text{bus}}$ in per unit for the circuit in Problem 7.14. Then invert $\boldsymbol{Y}_{\text{bus}}$ to obtain $\boldsymbol{Z}_{\text{bus}}$.

7.21 Figure 7.18 shows a system reactance diagram. (a) Draw the admittance diagram for the system by using source transformations. (b) Find the bus admittance matrix $\boldsymbol{Y}_{\text{bus}}$. (c) Find the bus impedance $\boldsymbol{Z}_{\text{bus}}$ matrix by inverting $\boldsymbol{Y}_{\text{bus}}$.

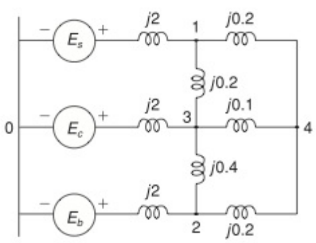


FIGURE 7.18
Problem 7.21

7.22 For the network shown in Figure 7.19, impedances labeled 1 through 6 are in per unit. (a) Determine $\boldsymbol{Y}_{\text{bus}}$, preserving all buses. (b) Using MATLAB or a similar computer program, invert $\boldsymbol{Y}_{\text{bus}}$ to obtain $\boldsymbol{Z}_{\text{bus}}$.

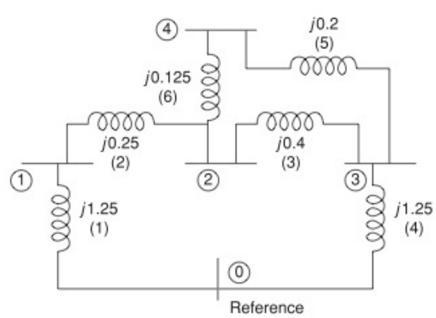


FIGURE 7.19
Problem 7.22

7.23 A single-line diagram of a four-bus system is shown in Figure 7.20, for which Z_{bus} is given below:

$$Z_{bus} = j\begin{bmatrix} 0.25 & 0.2 & 0.16 & 0.14 \\ 0.2 & 0.23 & 0.15 & 0.151 \\ 0.16 & 0.15 & 0.196 & 0.1 \\ 0.14 & 0.151 & 0.1 & 0.195 \end{bmatrix} \text{ per unit}$$

Let a three-phase fault occur at bus 2 of the network.
(a) Calculate the initial symmetrical rms current in the fault.

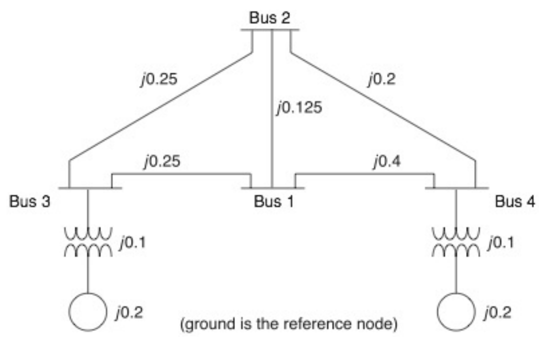
(b) Determine the voltages during the fault at buses 1, 3, and 4.

(c) Compute the fault currents contributed to bus 2 by the adjacent unfaulted buses 1, 3, and 4.

(d) Find the current flow in the line from bus 3 to bus 1. Assume the prefault voltage V_f at bus 2 to be $1\underline{/0°}$ p.u., and neglect all prefault currents.

FIGURE 7.20

Single-line diagram for Problem 7.23



PW **7.24** PowerWorld Simulator case Problem 7_24 models the system shown in Figure 7.14 with all data on a 1000 MVA base. Using PowerWorld Simulator, determine the current supplied by each generator and the per-unit bus voltage magnitudes at each bus for a fault at bus 3.

PW **7.25** Repeat Problem 7.24, except place the fault at bus 4.

PW **7.26** Repeat Problem 7.24, except place the fault midway between buses 2 and 3. Determining the values for line faults requires that the line be split with a fictitious bus added at the point of the fault. The original line's impedance is then allocated to the two new lines based on the fault location, which is 50% each for this problem. Fault calculations are then the same as for a bus fault. This is done automatically in PowerWorld Simulator by first right-clicking on a line, and then selecting Fault. The Fault dialog appears as before, except now the fault type is changed to In-Line Fault.

Set the location percentage field to 50% to model a fault midway between buses 2 and 4.

PW **7.27** One technique for limiting fault current is to place reactance in series with the generators. Such reactance can be modeled in PowerWorld Simulator by increasing the value of the generator's positive sequence internal impedance. For the Problem 7.24 case, how much per-unit reactance must be added to G2 to limit its maximum fault current to 2.5 per unit for all three-phase bus faults? Where is the location of the most severe bus fault?

PW **7.28** Using PowerWorld Simulator case Example 6_13, determine the per-unit current and actual current in amps supplied by each of the generators for a fault at the POPLAR69 bus. During the fault, what percentage of the system buses have voltage magnitudes below 0.75 per unit?

PW **7.29** Repeat Problem 7.28, except place the fault at the REDBUD69 bus.

PW **7.30** Using PowerWorld Simulator case Example 7_5, open the line connecting buses 4 and 5. Then, determine the per unit current supplied by the generator at bus 3 due a fault at bus 2.

SECTION 7.5

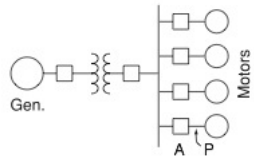
7.31 A three-phase circuit breaker has a 15.5-kV rated maximum voltage, 9.0-kA rated short-circuit current, and a 2.50-rated voltage range factor. (a) Determine the symmetrical interrupting capability at 10-kV and 5-kV operating voltages. (b) Can this breaker be safely installed at a three-phase bus where the symmetrical fault current is 10 kA, the operating voltage is 13.8 kV, and the (X/R) ratio is 12?

7.32 A 345-kV, three-phase transmission line has a 2.2-kA continuous current rating and a 2.5-kA maximum short-time overload rating with a 356-kV maximum operating voltage. The maximum symmetrical fault current on the line is 30 kA. Select a circuit breaker for this line from Table 7.10.

7.33 A 69-kV circuit breaker has a voltage range factor K = 1.25, a continuous current rating of 1200 A, and a rated short-circuit current of 19,000 A at the maximum rated voltage of 72.5 kV. Determine the maximum symmetrical interrupting capability of the breaker. Also, explain its significance at lower operating voltages.

7.34 As shown in Figure 7.21, a 25-MVA, 13.8-kV, 60-Hz, synchronous generator with $X_d'' = 0.15$ per unit is connected through a transformer to a bus that supplies four identical motors. The rating of the three-phase transformer is 25 MVA and 13.8/6.9 kV with a leakage reactance of 0.1 per unit. Each motor has a subtransient reactance $X_d'' = 0.2$ per unit on a base of 5 MVA and 6.9 kV. A three-phase fault occurs at point P, when the bus voltage at the motors is 6.9 kV. Determine (a) the subtransient fault current, (b) the subtransient current through breaker A, and (c) the symmetrical short-circuit interrupting current (as defined for circuit breaker applications) in the fault and in breaker A.

FIGURE 7.21
Problem 7.34



CASE STUDIES QUESTIONS

a. What are the four main types of wind-turbine generators (WTG)? How do WTGs differ from conventional generators?

b. Which type of WTG can produce the largest three-phase short-circuit current?

c. For which type of WTG can the short-circuit current be controlled? Why?

DESIGN PROJECT 3 (*CONTINUED*): POWER FLOW/ SHORT CIRCUITS

Additional time given: 3 weeks

Additional time required: 10 hours

This is a continuation of Design Project 3. Assignments 1 and 2 are given in Chapter 6.

Assignment 3: Symmetrical Short Circuits

For the single-line diagram that you have been assigned (Figure 6.13 or 6.14), convert the positive-sequence reactance data to per unit using the given base quantities. For synchronous machines, use subtransient reactance. Then using PowerWorld Simulator, create the machine, transmission line, and transformer input data files. Next, run the program to compute subtransient fault currents for a bolted three-phase-to-ground fault at bus 1, then at bus 2, then at bus 3, and so on. Also compute bus voltages during the faults and the positive-sequence bus impedance matrix. Assume 1.0 per-unit prefault voltage. Neglect prefault load currents and all losses.

Your output for this assignment consists of three input data files and three output data (fault currents, bus voltages, and the bus impedance matrix) files.

This project continues in Chapter 9.