PROBLEMS

SECTION 9.1

9.1 The single-line diagram of a three-phase power system is shown in Figure 9.17. Equipment ratings are given as follows:

Synchronous generators:

G1	1000 MVA	15 kV	$X''_d = X_2 = 0.18$, $X_0 = 0.07$ per unit
G2	1000 MVA	15 kV	$X''_d = X_2 = 0.20$, $X_0 = 0.10$ per unit
G3	500 MVA	13.8 kV	$X''_d = X_2 = 0.15$, $X_0 = 0.05$ per unit
G4	750 MVA	13.8 kV	$X''_d = 0.30$, $X_2 = 0.40$, $X_0 = 0.10$ per unit

Transformers:

T1	1000 MVA	15 kV Δ /765 kV Y	X = 0.10 per unit
T2	1000 MVA	15 kV Δ/765 kV Y	X = 0.10 per unit
T3	500 MVA	15kV Y/765kV Y	X = 0.12 per unit
T4	750 MVA	15 kV Y/765 kV Y	X = 0.11 per unit

Transmission lines:

1–2	765 kV	$X_1 = 50\ \Omega$, $X_0 = 150\ \Omega$
1–3	765 kV	$X_1 = 40\ \Omega$, $X_0 = 100\ \Omega$
2–3	765 kV	$X_1 = 40\ \Omega$, $X_0 = 100\ \Omega$

The inductor connected to Generator 3 neutral has a reactance of 0.05 per unit using generator 3 ratings as a base. Draw the zero-, positive-, and negative-sequence reactance diagrams using a 1000-MVA, 765-kV base in the zone of line 1–2. Neglect the Δ–Y transformer phase shifts.

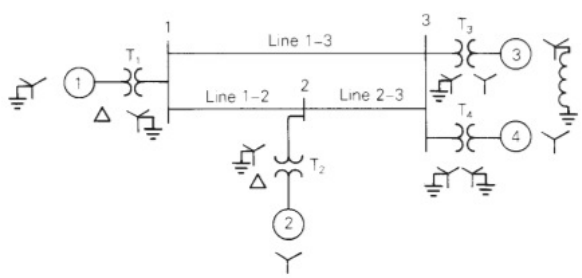


FIGURE 9.17 Problem 9.1

9.2 Faults at bus *n* in Problem 9.1 are of interest (the instructor selects $n = 1$, 2, or 3). Determine the Thévenin equivalent of each sequence network as viewed from the fault bus. Prefault voltage is 1.0 per unit. Prefault load currents and Δ–Y transformer phase shifts are neglected. *(Hint:* Use the Y–Δ conversion in Figure 2.33.)

9.3 Determine the subtransient fault current in per-unit and in kA during a bolted three-phase fault at the fault bus selected in Problem 9.2.

9.4 In Problem 9.1 and Figure 9.17, let 765 kV be replaced by 500 kV, keeping the rest of the data to be the same. Repeat (a) Problems 9.1, (b) 9.2, and (c) 9.3.

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

Generator G1:	500 MVA, 13.8 kV, $X_d'' = X_2 = 0.20$, $X_0 = 0.10$ per unit
Generator G2:	750 MVA, 18 kV, $X_d'' = X_2 = 0.18$, $X_0 = 0.09$ per unit
Generator G3:	1000 MVA, 20 kV, $X_d'' = 0.17$, $X_2 = 0.20$, $X_0 = 0.09$ per unit
Transformer T1:	500 MVA, 13.8 kV Δ /500 kV Y, X = 0.12 per unit
Transformer T2:	750 MVA, 18 kV Δ/500 kV Y, X = 0.10 per unit
Transformer T3:	1000 MVA, 20 kV Δ/500 kV Y, X = 0.10 per unit
Each line:	$X_1 = 50$ ohms, $X_0 = 150$ ohms

The inductor connected to generator G3 neutral has a reactance of 0.028 Ω. Draw the zero-, positive-, and negative-sequence reactance diagrams using a 1000-MVA, 20-kV base in the zone of generator G3. Neglect Δ–Y transformer phase shifts.

9.6 Faults at bus *n* in Problem 9.5 are of interest (the instructor selects $n = 1$, 2, 3, or 4). Determine the Thévenin equivalent of each sequence network as viewed from the fault bus. Prefault voltage is 1.0 per unit. Prefault load currents and Δ–Y phase shifts are neglected.

9.7 Determine the subtransient fault current in per-unit and in kA during a bolted three-phase fault at the fault bus selected in Problem 9.6.

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

Generator G1:	50 MVA, 12 kV, $X_d'' = X_2 = 0.20$, $X_0 = 0.10$ per unit
Generator G2:	100 MVA, 15 kV, $X_d'' = 0.2$, $X_2 = 0.23$, $X_0 = 0.1$ per unit
Transformer T1:	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:	$X_1 = 40$ ohms, $X_0 = 100$ ohms

Draw the zero-, positive-, and negative-sequence reactance diagrams using a 100-MVA, 15-kV base in the zone of generator G2. Neglect Δ–Y transformer phase shifts.

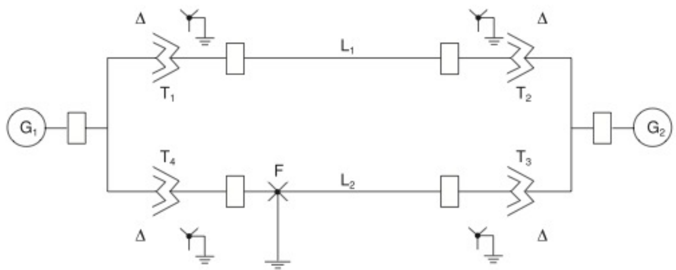


FIGURE 9.18

Problem 9.11

9.9 Faults at bus *n* in Problem 9.8 are of interest (the instructor selects n = 1, 2, 3, 4, or 5). Determine the Thévenin equivalent of each sequence network as viewed from the fault bus. Prefault voltage is 1.0 per unit. Prefault load currents and Δ–Y phase shifts are neglected.

9.10 Determine the subtransient fault current in per-unit and in kA during a bolted three-phase fault at the fault bus selected in Problem 9.9.

9.11 Consider the system shown in Figure 9.18. (a) As viewed from the fault at F, determine the Thévenin equivalent of each sequence network. Neglect Δ–Y phase shifts. (b) Compute the fault currents for a balanced three-phase fault at fault point F through three fault impedances $Z_{FA} = Z_{FB} = Z_{FC} = j0.5$ per unit. Equipment data in per-unit on the same base are given as follows:

Synchronous generators:

G1	$X_1 = 0.2$	$X_2 = 0.12$	$X_0 = 0.06$
G2	$X_1 = 0.33$	$X_2 = 0.22$	$X_0 = 0.066$

Transformers:

T1	$X_1 = X_2 = X_0 = 0.2$
T2	$X_1 = X_2 = X_0 = 0.225$
T3	$X_1 = X_2 = X_0 = 0.27$
T4	$X_1 = X_2 = X_0 = 0.16$

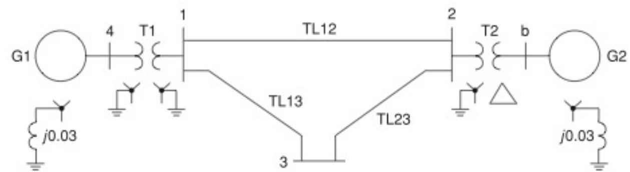
Transmission lines:

L1	$X_1 = X_2 = 0.14$	$X_0 = 0.3$
L1	$X_1 = X_2 = 0.35$	$X_0 = 0.6$

9.12 Equipment ratings and per-unit reactances for the system shown in Figure 9.19 are given as follows:

FIGURE 9.19

Problem 9.12



Synchronous generators:

G1	100 MVA	25 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$
G2	100 MVA	13.8 kV	$X_1 = X_2 = 0.2$	$X_0 = 0.05$

Transformers:

T1	100 MVA	25/230 kV	$X_1 = X_2 = X_0 = 0.05$
T2	100 MVA	13.8/230 kV	$X_1 = X_2 = X_0 = 0.05$

Transmission lines:

TL12	100 MVA	230 kV	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL13	100 MVA	230 kV	$X_1 = X_2 = 0.1$	$X_0 = 0.3$
TL23	100 MVA	230 kV	$X_1 = X_2 = 0.1$	$X_0 = 0.3$

Using a 100-MVA, 230-kV base for the transmission lines, draw the per-unit sequence networks and reduce them to their Thévenin equivalents, "looking in" at bus 3. Neglect Δ–Y phase shifts. Compute the fault currents for a bolted three-phase fault at bus 3.

9.13 Consider the oneline diagram of a simple power system shown in Figure 9.20. System data in per-unit on a 100-MVA base are given as follows:

Synchronous generators:

G1	100 MVA	20 kV	$X_1 = X_2 = 0.15$	$X_0 = 0.05$
G2	100 MVA	20 kV	$X_1 = X_2 = 0.15$	$X_0 = 0.05$

Transformers:

T1	100 MVA	20/220 kV	$X_1 = X_2 = X_0 = 0.1$
T2	100 MVA	20/220 kV	$X_1 = X_2 = X_0 = 0.1$

Transmission lines:

L12	100 MVA	220 kV	$X_1 = X_2 = 0.125$	$X_0 = 0.3$
L13	100 MVA	220 kV	$X_1 = X_2 = 0.15$	$X_0 = 0.35$
L23	100 MVA	220 kV	$X_1 = X_2 = 0.25$	$X_0 = 0.7125$

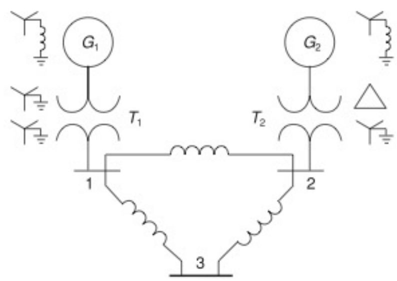


FIGURE 9.20

Problem 9.13

The neutral of each generator is grounded through a current-limiting reactor of 0.08333 per unit on a 100-MVA base. All transformer neutrals are solidly grounded. The generators are operating no-load at their rated voltages and rated frequency with their EMFs in phase. Determine the fault current for a balanced three-phase fault at bus 3 through a fault impedance $Z_F = 0.1$ per unit on a 100-MVA base. Neglect Δ–Y phase shifts.

SECTIONS 9.2–9.4

9.14 Determine the subtransient fault current in per-unit and in kA, as well as the per-unit line-to-ground voltages at the fault bus for a bolted single line-to-ground fault at the fault bus selected in Problem 9.2.

9.15 Repeat Problem 9.14 for a single line-to-ground arcing fault with arc impedance $Z_F = 15 + j0\ \Omega$.

9.16 Repeat Problem 9.14 for a bolted line-to-line fault.

9.17 Repeat Problem 9.14 for a bolted double line-to-ground fault.

9.18 Repeat Problems 9.1 and 9.14 including Δ–Y transformer phase shifts. Assume American standard phase shift. Also calculate the sequence components and phase components of the contribution to the fault current from generator n ($n = 1, 2,$ or 3 as specified by the instructor in Problem 9.2).

9.19 (a) Repeat Problem 9.14 for the case of Problem 9.4 (b).

(b) Repeat Problem 9.19(a) for a single line-to-ground arcing fault with arc impedance $Z_F = (15 + j0)\ \Omega$.

(c) Repeat Problem 9.19(a) for a bolted line-to-line fault.

(d) Repeat Problem 9.19(a) for a bolted double line-to-ground fault.

(e) Repeat Problems 9.4(a) and 9.19(a) including Δ–Y transformer phase shifts. Assume American standard phase shift. Also calculate the sequence components and phase components of the contribution to the fault current from generator n ($n = 1, 2,$ or 3) as specified by the instructor in Problem 9.4(b).

9.20 A 500-MVA, 13.8-kV synchronous generator with $X_d'' = X_2 = 0.20$ and $X_0 = 0.05$ per unit is connected to a 500-MVA, 13.8-kV Δ/500-kV Y transformer with 0.10 per-unit leakage reactance. The generator and transformer neutrals are solidly grounded. The generator is operated at no-load and rated voltage, and the high-voltage side of the transformer is disconnected from the power system. Compare the subtransient fault currents for the following bolted faults at the transformer high-voltage terminals: three-phase fault, single line-to-ground fault, line-to-line fault, and double line-to-ground fault.

9.21 Determine the subtransient fault current in per-unit and in kA, as well as contributions to the fault current from each line and transformer connected to the fault bus for a bolted single line-to-ground fault at the fault bus selected in Problem 9.6.

9.22 Repeat Problem 9.21 for a bolted line-to-line fault.

9.23 Repeat Problem 9.21 for a bolted double line-to-ground fault.

9.24 Determine the subtransient fault current in per-unit and in kA, as well as contributions to the fault current from each line, transformer, and generator connected to the fault bus for a bolted single line-to-ground fault at the fault bus selected in Problem 9.9.

9.25 Repeat Problem 9.24 for a single line-to-ground arcing fault with arc impedance $Z_F = 0 + j0.1$ per unit.

9.26 Repeat Problem 9.24 for a bolted line-to-line fault.

9.27 Repeat Problem 9.24 for a bolted double line-to-ground fault.

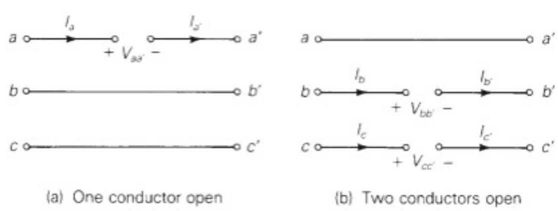
9.28 As shown in Figure 9.21 (a), two three-phase buses *abc* and *a′b′c′* are interconnected by short circuits between phases *b* and *b′* and between *c* and *c′*, with an open circuit between phases *a* and *a′*. The fault conditions in the phase domain are $I_a = I_{a'} = 0$ and $V_{bb'} = V_{cc'} = 0$. Determine the fault conditions in the sequence domain and verify the interconnection of the sequence networks as shown in Figure 9.15 for this one-conductor-open fault.

9.29 Repeat Problem 9.28 for the two-conductors-open fault shown in Figure 9.21(b). The fault conditions in the phase domain are

$$I_b = I_{b'} = I_c = I_{c'} = 0 \text{ and } V_{aa'} = 0$$

FIGURE 9.21

Problems 9.28 and 9.29: open conductor faults



9.30 For the system of Problem 9.11, compute the fault current and voltages at the fault for the following faults at point F: (a) a bolted single line-to-ground fault; (b) a line-to-line fault through a fault impedance $Z_F = j0.05$ per unit; (c) a double line-to-ground fault from phase B to C to ground, where phase B has a fault impedance $Z_F = j0.05$ per unit, phase C also has a fault impedance $Z_F = j0.05$ per unit, and the common line-to-ground fault impedance is $Z_G = j0.033$ per unit.

9.31 For the system of Problem 9.12, compute the fault current and voltages at the fault for the following faults at bus 3: (a) a bolted single line-to-ground fault, (b) a bolted line-to-line fault, (c) a bolted double line-to-ground fault. Also, for the single line-to-ground fault at bus 3, determine the currents and voltages at the terminals of generators Gl and G2.

9.32 For the system of Problem 9.13, compute the fault current for the following faults at bus 3: (a) a single line-to-ground fault through a fault impedance $Z_F = j0.1$ per unit, (b) a line-to-line fault through a fault impedance $Z_F = j0.1$ per unit, (c) a double line-to-ground fault through a common fault impedance to ground $Z_F = j0.1$ per unit.

9.33 For the three-phase power system with single-line diagram shown in Figure 9.22, equipment ratings and per-unit reactances are given as follows:

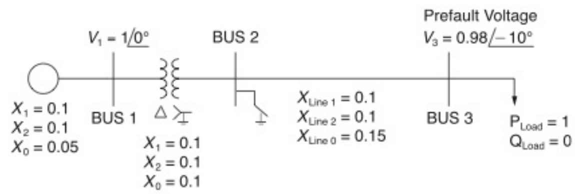
Machines 1 and 2:	100 MVA	20 kV	$X_1 = X_2 = 0.2$
	$X_0 = 0.04$	$X_n = 0.04$	
Transformers 1 and 2:	100 MVA	20Δ/345Y kV	
	$X_1 = X_2 = X_0 = 0.08$		

Select a base of 100 MVA, 345 kV for the transmission line. On that base, the series reactances of the line are $X_1 = X_2 = 0.15$ and $X_0 = 0.5$ per unit. With a nominal system voltage of 345 kV at bus 3, machine 2 is operating as a motor drawing 50 MVA at 0.8 power factor lagging. Compute the change in voltage at bus 3 when the transmission line undergoes (a) a one-conductor-open fault, (b) a two-conductor-open fault along its span between buses 2 and 3.

9.34 At the general three-phase bus shown in Figure 9.7(a) of the text, consider a simultaneous single line-to-ground fault on phase *a* and line-to-line fault between phases *b* and *c*, with no fault impedances. Obtain the sequence-network interconnection satisfying the current and voltage constraints.

FIGURE 9.22
Problem 9.33

FIGURE 9.23
Problem 9.36



9.35 Thévenin equivalent sequence networks looking into the faulted bus of a power system are given with $Z_1 = j0.15$, $Z_2 = j0.15$, $Z_0 = j0.2$, and $E_1 = 1\angle{0°}$ per unit. Compute the fault currents and voltages for the following faults occurring at the faulted bus:

(a) Balanced three-phase fault

(b) Single line-to-ground fault

(c) Line-line fault

(d) Double line-to-ground fault

Which is the worst fault from the viewpoint of the fault current?

9.36 The single-line diagram of a simple power system is shown in Figure 9.23 with per unit values. Determine the fault current at bus 2 for a three-phase fault. Ignore the effect of phase shift.

9.37 Consider a simple circuit configuration shown in Figure 9.24 to calculate the fault currents I_1, I_2, and I with the switch closed.

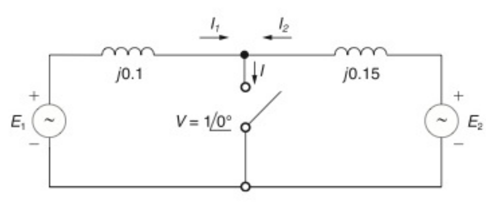
(a) Compute E_1 and E_2 prior to the fault based on the prefault voltage $V = 1\angle{0°}$ and then, with the switch closed, determine I_1, I_2, and I.

(b) Start by ignoring prefault currents, with $E_1 = E_2 = 1\angle{0°}$. Then superimpose the load currents, which are the prefault currents, $I_1 = -I_2 = 1\angle{0°}$. Compare the results with those of part (a).

SECTION 9.5

9.38 The zero-, positive-, and negative-sequence bus impedance matrices for a three-bus three-phase power system are

FIGURE 9.24
Problem 9.37



$$Z_{\text{bus}\,0} = j\begin{bmatrix} 0.10 & 0 & 0 \\ 0 & 0.20 & 0 \\ 0 & 0 & 0.10 \end{bmatrix} \quad \text{per unit}$$

$$Z_{\text{bus}\,1} = Z_{bus\,2} = j\begin{bmatrix} 0.12 & 0.08 & 0.04 \\ 0.08 & 0.12 & 0.06 \\ 0.04 & 0.06 & 0.08 \end{bmatrix}$$

Determine the per-unit fault current and per-unit voltage at bus 2 for a bolted three-phase fault at bus 1. The prefault voltage is 1.0 per unit.

9.39 Repeat Problem 9.38 for a bolted single line-to-ground fault at bus 1.

9.40 Repeat Problem 9.38 for a bolted line-to-line fault at bus 1.

9.41 Repeat Problem 9.38 for a bolted double line-to-ground fault at bus 1.

9.42 (a) Compute the 3 × 3 per-unit zero-, positive-, and negative-sequence bus impedance matrices for the power system given in Problem 9.1. Use a base of 1000 MVA and 765 kV in the zone of line 1–2.

(b) Using the bus impedance matrices determined in Problem 9.42, verify the fault currents for the faults given in Problems 9.3, 9.14, 9.15, 9.16, and 9.17.

9.43 The zero-, positive-, and negative-sequence bus impedance matrices for a two-bus three-phase power system are

$$Z_{\text{bus}\,0} = j\left[\begin{array}{c|c} 0.10 & 0 \\ \hline 0 & 0.10 \end{array}\right] \quad \text{per unit}$$

$$Z_{\text{bus}\,1} = Z_{\text{bus}\,2} = j\left[\begin{array}{c|c} 0.20 & 0.10 \\ \hline 0.10 & 0.30 \end{array}\right] \quad \text{per unit}$$

Determine the per-unit fault current and per-unit voltage at bus 2 for a bolted three-phase fault at bus 1. The prefault voltage is 1.03 per unit.

9.44 Repeat Problem 9.43 for a bolted single line-to-ground fault at bus 1.

9.45 Repeat Problem 9.43 for a bolted line-to-line fault at bus 1.

9.46 Repeat Problem 9.43 for a bolted double line-to-ground fault at bus 1.

9.47 Compute the 3 × 3 per-unit zero-, positive-, and negative-sequence bus impedance matrices for the power system given in Problem 4(a). Use a base of 1000 MVA and 500 kV in the zone of line 1–2.

9.48 Using the bus impedance matrices determined in Problem 9.47, verify the fault currents for the faults given in Problems 9.4(b), 9.4(c), and 9.19 (a through d).

9.49 Compute the 4 × 4 per-unit zero-, positive-, and negative-sequence bus impedance matrices for the power system given in Problem 9.5. Use a base of 1000 MVA and 20 kV in the zone of generator G3.

9.50 Using the bus impedance matrices determined in Problem 9.42, verify the fault currents for the faults given in Problems 9.7, 9.21, 9.22, and 9.23.

9.51 Compute the 5 × 5 per-unit zero-, positive-, and negative-sequence bus impedance matrices for the power system given in Problem 9.8. Use a base of 100 MVA and 15 kV in the zone of generator G2.

9.52 Using the bus impedance matrices determined in Problem 9.51, verify the fault currents for the faults given in Problems 9.10, 9.24, 9.25, 9.26, and 9.27.

9.53 The positive-sequence impedance diagram of a five-bus network with all values in per-unit on a 100-MVA base is shown in Figure 9.25. The generators at buses 1 and 3 are rated 270 and 225 MVA, respectively. Generator reactances include subtransient values plus reactances of the transformers connecting them to the buses. The turns ratios of the transformers are such that the voltage base in each generator circuit is equal to the voltage rating of the generator. (a) Develop the positive-sequence bus admittance matrix $\boldsymbol{Y}_{bus\,1}$. (b) Using MATLAB or another computer program, invert $\boldsymbol{Y}_{bus\,1}$ to obtain $\boldsymbol{Z}_{bus\,1}$. (c) Determine the subtransient current for a three-phase fault at bus 4 and the contributions to the fault current from each line. Neglect prefault currents and assume a prefault voltage of 1.0 per unit.

9.54 For the five-bus network shown in Figure 9.25, a bolted single-line-to-ground fault occurs at the bus 2 end of the transmission line between buses 1 and 2. The fault causes the circuit breaker at the bus 2 end of the line to open, but all other breakers remain closed. The fault is shown in Figure 9.26. Compute the subtransient fault current with the circuit breaker at the bus-2 end of the faulted line open. Neglect prefault current and assume a prefault voltage of 1.0 per unit.

9.55 A single-line diagram of a four-bus system is shown in Figure 9.27. Equipment ratings and per-unit reactances are given as follows.

Machines 1 and 2:	100 MVA	20 kV	$X_1 = X_2 = 0.2$
	$X_0 = 0.04$	$X_n = 0.05$	
Transformers T_1 and T_2:	100 MVA	20Δ/345Y kV	
	$X_1 = X_2 = X_0 = 0.08$		

FIGURE 9.25

Problems 9.53 and 9.54