

clear % clears all variables from the workspace.
 basemva = 100; accuracy = 0.001; maxiter = 20;

busdata = [same as in Example 6.9];
 linedata = [same as in Example 6.9];

lfybus % Forms the bus admittance matrix
 decouple % Power flow solution by fast decoupled method
 busout % Prints the power flow solution on the screen
 lineflow % Computes and displays the line flow and losses

The output of decouple is

Power Flow Solution by Fast Decoupled Method

Maximum Power mismatch = 0.000919582

No. of iterations = 15

Bus No.	Voltage Mag.	Angle Degree	Load MW	Load Mvar	Generation MW	Generation Mvar	Injected MW	Injected Mvar
1	1.060	0.000	0.000	0.000	260.998	-17.021	0.00	0.00
2	1.043	-5.497	21.700	12.700	40.000	48.822	0.00	0.00
3	1.022	-8.004	2.400	1.200	0.000	0.000	0.00	0.00
4	1.013	-9.662	7.600	1.600	0.000	0.000	0.00	0.00
5	1.010	-14.381	94.200	19.000	0.000	35.975	0.00	0.00
6	1.012	-11.398	0.000	0.000	0.000	0.000	0.00	0.00
7	1.003	-13.149	22.800	10.900	0.000	0.000	0.00	0.00
8	1.010	-12.115	30.000	30.000	0.000	30.828	0.00	0.00
9	1.051	-14.434	0.000	0.000	0.000	0.000	0.00	0.00
10	1.044	-16.024	5.800	2.000	0.000	0.000	19.00	0.00
11	1.082	-14.434	0.000	0.000	0.000	16.120	0.00	0.00
12	1.057	-15.303	11.200	7.500	0.000	0.000	0.00	0.00
13	1.071	-15.303	0.000	0.000	0.000	10.421	0.00	0.00
14	1.042	-16.198	6.200	1.600	0.000	0.000	0.00	0.00
15	1.038	-16.276	8.200	2.500	0.000	0.000	0.00	0.00
16	1.045	-15.881	3.500	1.800	0.000	0.000	0.00	0.00
17	1.039	-16.188	9.000	5.800	0.000	0.000	0.00	0.00
18	1.028	-16.882	3.200	0.900	0.000	0.000	0.00	0.00
19	1.025	-17.051	9.500	3.400	0.000	0.000	0.00	0.00
20	1.029	-16.852	2.200	0.700	0.000	0.000	0.00	0.00
21	1.032	-16.468	17.500	11.200	0.000	0.000	0.00	0.00
22	1.033	-16.454	0.000	0.000	0.000	0.000	0.00	0.00
23	1.027	-16.661	3.200	1.600	0.000	0.000	0.00	0.00
24	1.022	-16.829	8.700	6.700	0.000	0.000	0.00	4.30
25	1.019	-16.423	0.000	0.000	0.000	0.000	0.00	0.00
26	1.001	-16.840	3.500	2.300	0.000	0.000	0.00	0.00

27	1.026	-15.912	0.000	0.000	0.000	0.000	0.000	0.00
28	1.011	-12.057	0.000	0.000	0.000	0.000	0.000	0.00
29	1.006	-17.136	2.400	0.900	0.000	0.000	0.000	0.00
30	0.995	-18.014	10.600	1.900	0.000	0.000	0.000	0.00
Total			283.400	126.200	300.998	125.145	23.30	

The output of the lineflow is the same as the line flow output of Example 6.9 with the power mismatch as dictated by the fast decoupled method.

PROBLEMS

6.1. A power system network is shown in Figure 6.17. The generators at buses 1 and 2 are represented by their equivalent current sources with their reactances in per unit on a 100-MVA base. The lines are represented by π model where series reactances and shunt reactances are also expressed in per unit on a 100 MVA base. The loads at buses 3 and 4 are expressed in MW and Mvar.

(a) Assuming a voltage magnitude of 1.0 per unit at buses 3 and 4, convert the loads to per unit impedances. Convert network impedances to admittances and obtain the bus admittance matrix by inspection.

(b) Use the function $Y = ybus(zdata)$ to obtain the bus admittance matrix. The function argument $zdata$ is a matrix containing the line bus numbers, resistance and reactance. (See Example 6.1.)

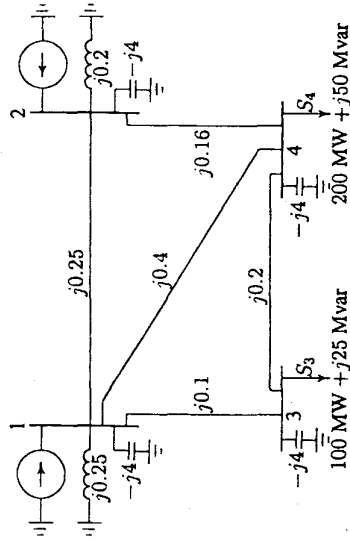


FIGURE 6.17 One-line diagram for Problem 6.1.

6.2. A power system network is shown in Figure 6.18. The values marked are impedances in per unit on a base of 100 MVA. The currents entering buses 1 and 2 are

$$I_1 = 1.38 - j2.72 \text{ pu}$$

$$I_2 = 0.69 - j1.36 \text{ pu}$$

- (a) Determine the bus admittance matrix by inspection.
 (b) Use the function $Y = ybus(zdata)$ to obtain the bus admittance matrix. The function argument *zdata* is a matrix containing the line bus numbers, resistance and reactance. (See Example 6.1.) Write the necessary *MATLAB* commands to obtain the bus voltages.

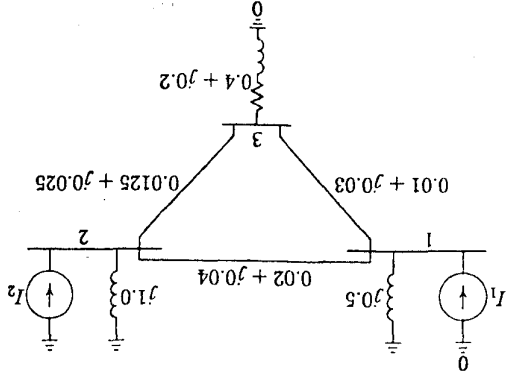


FIGURE 6.18

One-line diagram for Problem 6.2.

6.3. Use Gauss-Seidel method to find the solution of the following equations

$$x_1 + x_1 x_2 = 10$$

$$x_1 + x_2 = 6$$

with the following initial estimates

(a) $x_1^{(0)} = 1$ and $x_2^{(0)} = 1$
 (b) $x_1^{(0)} = 1$ and $x_2^{(0)} = 2$

Continue the iterations until $|\Delta x_1^{(k)}|$ and $|\Delta x_2^{(k)}|$ are less than 0.001.

6.4. A fourth-order polynomial equation is given by

$$x^4 - 21x^3 + 147x^2 - 379x + 252 = 0$$

- (a) Use Newton-Raphson method and hand calculations to find one of the roots of the polynomial equation. Start with the initial estimate of $x^{(0)} = 0$ and continue until $|\Delta x^{(k)}| < 0.001$.

- (b) Write a *MATLAB* program to find the roots of the above polynomial by Newton-Raphson method. The program should prompt the user to input the initial estimate. Run using the initial estimates of 0, 3, 6, 10.

- (c) Check your answers using the *MATLAB* function $r = roots(A)$, where *A* is a row vector containing the polynomial coefficients in descending powers.

6.5. Use Newton-Raphson method and hand calculation to find the solution of the following equations:

$$x_1^2 - 2x_1 - x_2 = 3$$

$$x_1^2 + x_2^2 = 41$$

- (a) Start with the initial estimates of $x_1^{(0)} = 2$, $x_2^{(0)} = 3$. Perform three iterations.

- (b) Write a *MATLAB* program to find one of the solutions of the above equations by Newton-Raphson method. The program should prompt the user to input the initial estimates. Run the program with the above initial estimates.

6.6. In the power system network shown in Figure 6.19, bus 1 is a slack bus with

$V_1 = 1.070^\circ$ per unit and bus 2 is a load bus with $S_2 = 280 \text{ MW} + j60 \text{ Mvar}$. The line impedance on a base of 100 MVA is $Z = 0.02 + j0.04$ per unit.

- (a) Using Gauss-Seidel method, determine V_2 . Use an initial estimate of $V_2^{(0)} = 1.0 + j0.0$ and perform four iterations.

- (b) If after several iterations voltage at bus 2 converges to $V_2 = 0.90 - j0.10$, determine S_1 and the real and reactive power loss in the line.

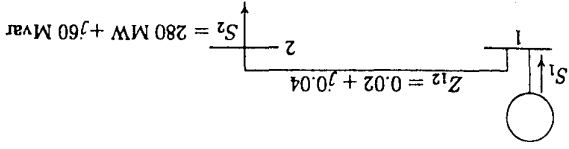


FIGURE 6.19

One-line diagram for Problem 6.6.

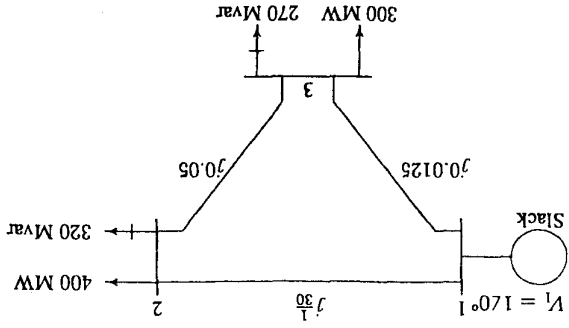


FIGURE 6.20 One-line diagram for Problem 6.7.

6.7. Figure 6.20 shows the one-line diagram of a simple three-bus power system with generation at bus 1. The voltage at bus 1 is $V_1 = 1.070^\circ$ per unit. The scheduled loads on buses 2 and 3 are marked on the diagram. Line impedances are marked in per unit on a 100-MVA base. For the purpose of hand calculations, line resistances and line charging susceptances are neglected.

(a) Using Gauss-Seidel method and initial estimates of $V_2^{(0)} = 1.0 + j0$ and $V_3^{(0)} = 1.0 + j0$, determine V_2 and V_3 . Perform two iterations.

(b) If after several iterations the bus voltages converge to

$$V_2 = 0.90 - j0.10 \text{ pu}$$

$$V_3 = 0.95 - j0.05 \text{ pu}$$

determine the line flows and line losses and the slack bus real and reactive power. Construct a power flow diagram and show the direction of the line flows.

(c) Check the power flow solution using the Gauss and other required programs. (Refer to Example 6.9.) Use a power accuracy of 0.00001 and an acceleration factor of 1.0.

6.8. Figure 6.21 shows the one-line diagram of a simple three-bus power system with generation at buses 1 and 3. The voltage at bus 1 is $V_1 = 1.02570^\circ$ per unit. Voltage magnitude at bus 3 is fixed at 1.03 pu with a real power generation of 300 MW. A load consisting of 400 MW and 200 Mvar is taken from bus 2. Line impedances are marked in per unit on a 100-MVA base. For the

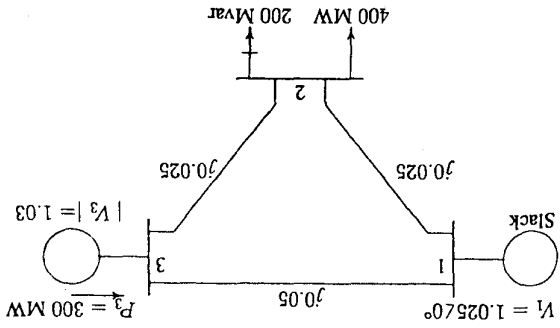


FIGURE 6.21 One-line diagram for Problem 6.8.

purpose of hand calculations, line resistances and line charging susceptances are neglected.

(a) Using Gauss-Seidel method and initial estimates of $V_2^{(0)} = 1.0 + j0$ and $V_3^{(0)} = 1.03 + j0$ pu, determine the phasor values of V_2 and V_3 . Perform two iterations.

(b) If after several iterations the bus voltages converge to

$$V_2 = 1.0012437 - 2.1^\circ = 1.000571 - j0.0366898 \text{ pu}$$

$$V_3 = 1.037136851^\circ = 1.029706 + j0.0246 \text{ pu}$$

determine the line flows and line losses and the slack bus real and reactive power. Construct a power flow diagram and show the direction of the line flows.

(c) Check the power flow solution using the Gauss and other required programs. (Refer to Example 6.9.)

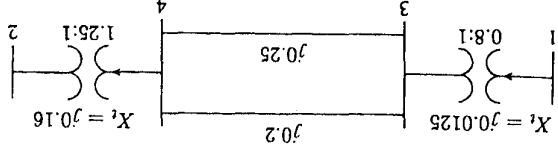


FIGURE 6.22 One-line diagram for Problem 6.9.

6.9. The one-line diagram of a four-bus power system is as shown in Figure 6.22. Reactances are given in per unit on a common MVA base. Transformers T_1 and T_2 have tap settings of 0.8:1, and 1.25:1 respectively. Obtain the bus admittance matrix.

6.10. In the two-bus system shown in Figure 6.23, bus 1 is a slack bus with $V_1 = 1.070^\circ$ pu. A load of 150 MW and 50 Mvar is taken from bus 2. The line admittance is $y_{12} = 107 - j73.74^\circ$ pu on a base of 100 MVA. The expression for real and reactive power at bus 2 is given by

$$P_2 = 10|V_2||V_1|\cos(106.26^\circ - \delta_2 + \delta_1) + 10|V_2|^2\cos(-73.74^\circ)$$

$$Q_2 = -10|V_2||V_1|\sin(106.26^\circ - \delta_2 + \delta_1) - 10|V_2|^2\sin(-73.74^\circ)$$

Using Newton-Raphson method, obtain the voltage magnitude and phase angle of bus 2. Start with an initial estimate of $|V_2|^{(0)} = 1.0$ pu and $\delta_2^{(0)} = 0^\circ$. Perform two iterations.

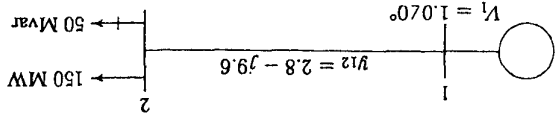


FIGURE 6.23

One-line diagram for Problem 6.10.

6.11. In the two-bus system shown in Figure 6.24, bus 1 is a slack bus with $V_1 = 1.070^\circ$ pu. A load of 100 MW and 50 Mvar is taken from bus 2. The line impedance is $z_{12} = 0.12 + j0.16$ pu on a base of 100 MVA. Using Newton-Raphson method, obtain the voltage magnitude and phase angle of bus 2. Start with an initial estimate of $|V_2|^{(0)} = 1.0$ pu and $\delta_2^{(0)} = 0^\circ$. Perform two iterations.

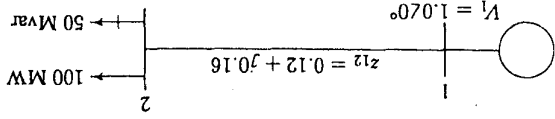


FIGURE 6.24

One-line diagram for Problem 6.11.

6.12. Figure 6.25 shows the one-line diagram of a simple three-bus power system with generation at buses 1 and 2. The voltage at bus 1 is $V = 1.070^\circ$ per unit. Voltage magnitude at bus 2 is fixed at 1.05 pu with a real power generation of 400 MW. A load consisting of 500 MW and 400 Mvar is taken from bus 3. Line admittances are marked in per unit on a 100 MVA base. For the purpose of hand calculations, line resistances and line charging susceptances are neglected.

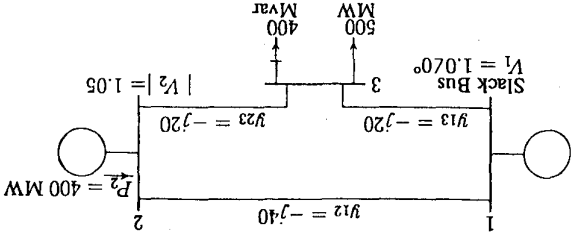


FIGURE 6.25

One-line diagram for Problem 6.12

(a) Show that the expression for the real power at bus 2 and real and reactive power at bus 3 are

$$P_2 = 40|V_2||V_1|\cos(90^\circ - \delta_2 + \delta_1) + 20|V_2||V_3|\cos(90^\circ - \delta_2 + \delta_3)$$

$$P_3 = 20|V_3||V_1|\cos(90^\circ - \delta_3 + \delta_1) + 20|V_3||V_2|\cos(90^\circ - \delta_3 + \delta_2)$$

$$Q_3 = -20|V_3||V_1|\sin(90^\circ - \delta_3 + \delta_1) - 20|V_3||V_2|\sin(90^\circ - \delta_3 + \delta_2) + 40|V_3|^2$$

(b) Using Newton-Raphson method, start with the initial estimates of $V_2^{(0)} = 1.0 + j0$ and $V_3^{(0)} = 1.0 + j0$, and keeping $|V_2| = 1.05$ pu, determine the phasor values of V_2 and V_3 . Perform two iterations.
 (c) Check the power flow solution for Problem 6.12 using Newton and other required programs. Assume the regulated bus (bus # 2) reactive power limits are between 0 and 600 Mvar.

6.13. For Problem 6.12:
 (a) Obtain the power flow solution using the fast decoupled algorithm. Perform two iterations.
 (b) Check the power flow solution for Problem 6.12 using decouple and other required programs. Assume the regulated bus (bus # 2) reactive power limits are between 0 and 600 Mvar.

6.14. The 26-bus power system network of an electric utility company is shown in Figure 6.26 (page 256). Obtain the power flow solution by the following

- methods:
- (a) Gauss-Seidel power flow (see Example 6.9).
 - (b) Newton-Raphson power flow (see Example 6.11).
 - (c) Fast decoupled power flow (see Example 6.13).

The load data is as follows.

Bus	Load		Bus	Load	
	No.	Mvar		No.	Mvar
1	51.0	41.0	14	24.0	12.0
2	22.0	15.0	15	70.0	31.0
3	64.0	50.0	16	55.0	27.0
4	25.0	10.0	17	78.0	38.0
5	50.0	30.0	18	153.0	67.0
6	76.0	29.0	19	75.0	15.0
7	0.0	0.0	20	48.0	27.0
8	0.0	0.0	21	46.0	23.0
9	89.0	50.0	22	45.0	22.0
10	0.0	0.0	23	25.0	12.0
11	25.0	15.0	24	54.0	27.0
12	89.0	48.0	25	28.0	13.0
13	31.0	15.0	26	40.0	20.0

Voltage magnitude, generation schedule, and the reactive power limits for the regulated buses are tabulated below. Bus 1, whose voltage is specified as $V_1 = 1.02570$, is taken as the slack bus.

GENERATION DATA			
Bus	Voltage	Generation	
		Mvar	Min. Max.
1	1.025	40.0	250.0
2	1.020	79.0	40.0
3	1.025	20.0	40.0
4	1.050	100.0	40.0
5	1.045	300.0	40.0
26	1.015	60.0	15.0

The Mvar of the shunt capacitors installed at substations and the transformer tap settings are given below.

LINE AND TRANSFORMER DATA										
Bus	Bus	No.	No.	$R, \frac{1}{2}B,$	$X, \frac{1}{2}B,$	pu	pu	No.	No.	pu
1	2	0.0005	0.0048	0.0300	10	22	0.0069	0.0298	0.005	
1	18	0.0013	0.0110	0.0600	11	25	0.0960	0.2700	0.010	
2	2	0.0103	0.0586	0.0180	12	14	0.0327	0.0802	0.000	
2	3	0.0014	0.0513	0.0500	11	26	0.0165	0.0970	0.004	
2	8	0.0074	0.0321	0.0390	12	15	0.0180	0.0598	0.000	
2	13	0.0035	0.0967	0.0250	13	14	0.0046	0.0271	0.001	
2	26	0.0323	0.1967	0.0000	13	15	0.0116	0.0610	0.000	
3	13	0.0007	0.0054	0.0005	13	16	0.0179	0.0888	0.001	
4	8	0.0008	0.0240	0.0001	14	15	0.0069	0.0382	0.000	
4	12	0.0016	0.0207	0.0150	15	16	0.0209	0.0512	0.000	
5	6	0.0069	0.0300	0.0990	16	17	0.0990	0.0600	0.000	
6	6	0.0050	0.0900	0.0226	19	24	0.0300	0.1250	0.002	
6	18	0.0037	0.0222	0.0012	17	21	0.2290	0.4450	0.000	
6	19	0.0035	0.0660	0.0450	19	23	0.0300	0.1310	0.000	
6	11	0.0097	0.0570	0.0001	17	18	0.0032	0.0600	0.038	
7	7	0.0053	0.0306	0.0010	16	20	0.0239	0.0585	0.000	
7	8	0.0012	0.0069	0.0001	19	25	0.1190	0.2249	0.004	
7	9	0.0009	0.0429	0.0250	20	21	0.0657	0.1570	0.000	
8	12	0.0020	0.0180	0.0200	20	22	0.0150	0.0366	0.000	
9	10	0.0010	0.0493	0.0010	21	24	0.0476	0.1510	0.000	
10	12	0.0024	0.0132	0.0100	22	23	0.0290	0.0990	0.000	
10	19	0.0547	0.2360	0.0000	22	24	0.0310	0.0880	0.000	
20	0.0066	0.0160	0.0010	23	25	0.0987	0.1168	0.000		

Bus No.	Mvar
1	4.0
4	2.0
5	5.0
6	2.0
11	1.5
12	2.0
15	0.5
19	5.0

Designation	Tap Setting
2-3	0.960
2-13	0.960
3-13	1.017
4-8	1.050
4-12	1.050
6-19	0.950
7-9	0.950

The line and transformer data containing the series resistance and reactance on a 100-MVA base are tabulated below.

OPTIMAL DISPATCH
OF GENERATION

7.1 INTRODUCTION

The formulation of power flow problem and its solutions were discussed in Chapter 6. One type of bus in the power flow was the voltage-controlled bus, where real power generation and voltage magnitude were specified. The power flow solution provided the voltage phase angle and the reactive power generation. In a practical power system, the power plants are not located at the same distance from the center of loads and their fuel costs are different. Also, under normal operating conditions, the generation capacity is more than the total load demand and losses. Thus, there are many options for scheduling generation. In an interconnected power system, the objective is to find the real and reactive power scheduling of each power plant in such a way as to minimize the operating cost. This means that the generator's real and reactive power are allowed to vary within certain limits so as to meet a particular load demand with minimum fuel cost. This is called the *optimal power flow* (OPF) problem. The OPF is used to optimize the power flow solution of large scale power system. This is done by minimizing selected objective functions while maintaining an acceptable system performance in terms of generator capability limits and the output of the compensating devices. The objective functions, also

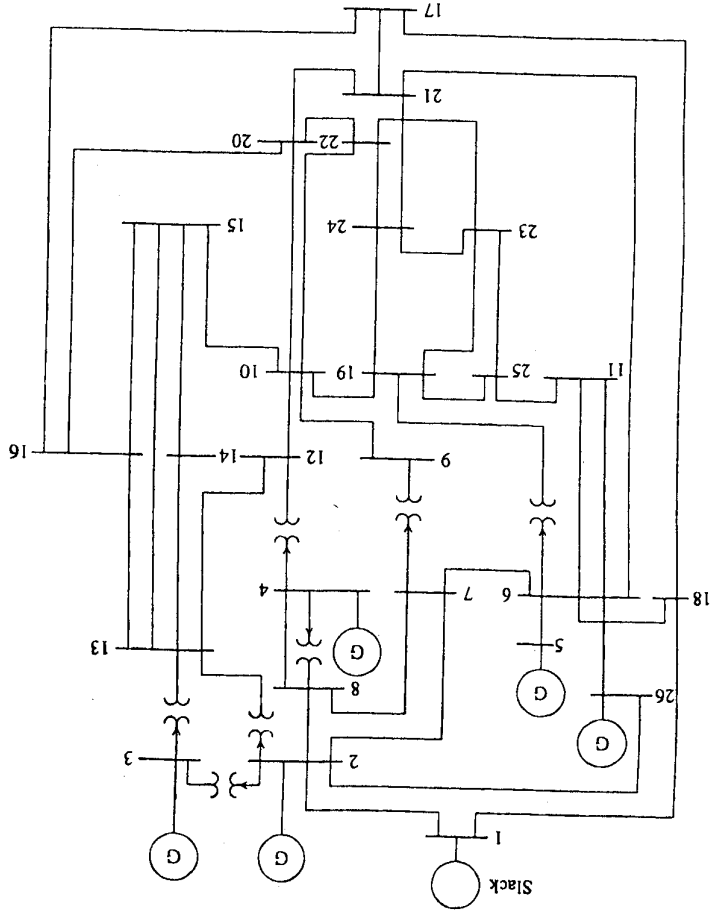


FIGURE 6.26
One-line diagram for Problem 6.14.