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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

POWER SYSTEM ANALYSIS ASSIGNMENT REPORT

ASSIGNMENT TITLE:

IEEE 14-BUS TEST SYSTEM POWER FLOW ANALYSIS

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1. Power Flow Analysis Methodology and Software

In this study, the MATLAB environment and the MATPOWER library infrastructure were used to perform power flow analysis on the IEEE 14-Bus test system. However, instead of using black-box solvers such as MATPOWER's standard runpf command, a customized Newton-Raphson solver structure was developed to prove a comprehensive understanding of the algorithm's internal operations.

Important Note: This analysis method will not work in MATLAB unless MATPOWER is installed.

The developed solution algorithm is modular and consists of three main .m files:

1. ieee_bus_case.m (Data File): This file has the system's topological data, bus types, line parameters, and generator limits, structured according to MATPOWER standards (the mpc structure).
2. newton.m (Solver Function): This is the core function where the Newton-Raphson iterations are managed. Inside this function, specific MATPOWER core functions were used:

    - makeYbus: To construct the Bus Admittance Matrix (Y-Bus),
    - makeSbus: To generate the complex power injection vector,
    - newtonpf: To execute the Newton-Raphson iterations.

Additionally, a custom injection_helper structure was integrated in this file to manage voltage-dependent load handling.

3. ieee_bus_case_test.m (Main Execution File): This is the main script that starts the analysis, performs post-processing on the results, calculates line losses, and reports the findings to both the console and an external .txt file.

Through this method, the entire process from the formation of the admittance matrix to the solution of the Jacobian matrix was explicitly controlled and analyzed.

2. System Modelling and Bus Data

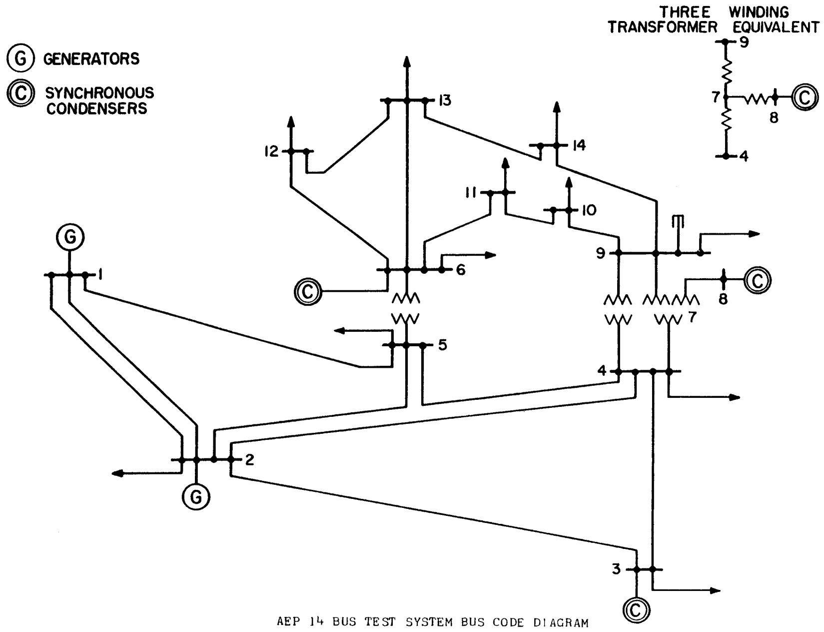

Figure 1: IEEE 14-Bus System Single Line Diagram

Bus No	Bus Voltage (p.u.)	Generation P (MW)	Generation Q (MVAr)	Load P (MW)	Load Q (MVAr)
1	1.060	0.0	0.0	0.0	0.0
2	1.045	40.0	42.4	21.7	12.7
3	1.010	0.0	23.4	94.2	19.0
4	1.000	0.0	0.0	47.8	-3.9
5	1.000	0.0	0.0	7.6	1.6
6	1.070	0.0	12.2	11.2	7.5
7	1.000	0.0	0.0	0.0	0.0
8	1.090	0.0	17.4	0.0	0.0
9	1.000	0.0	0.0	29.5	16.6
10	1.000	0.0	0.0	9.0	5.8
11	1.000	0.0	0.0	3.5	1.8
12	1.000	0.0	0.0	6.1	1.6
13	1.000	0.0	0.0	13.5	5.8
14	1.000	0.0	0.0	14.9	5.0

Table 1: Bus Data

Line (From-To)	Line Impedance R (p.u.)	Line Impedance X (p.u.)	Line Charging B (p.u.)
1-2	0.01938	0.05917	0.0528
1-5	0.05403	0.22304	0.0492
2-3	0.04699	0.19797	0.0438
2-4	0.05811	0.17632	0.0340
2-5	0.05695	0.17388	0.0346
3-4	0.06701	0.17103	0.0128
4-5	0.01335	0.04211	0.0000
4-7	0.00000	0.20912	0.0000
4-9	0.00000	0.55618	0.0000
5-6	0.00000	0.25202	0.0000
6-11	0.09498	0.19890	0.0000
6-12	0.12291	0.25581	0.0000
6-13	0.06615	0.13027	0.0000
7-8	0.00000	0.17615	0.0000
7-9	0.00000	0.11001	0.0000
9-10	0.03181	0.08450	0.0000
9-14	0.12711	0.27038	0.0000
10-11	0.08205	0.19207	0.0000
12-13	0.22092	0.19988	0.0000
13-14	0.17093	0.34802	0.0000

Table 2: Branch Data

The IEEE 14-Bus system analyzed in this report was modelled based on the Single Line Diagram provided in Figure 1. The system consists of 1 Slack (Swing) Bus, 4 PV (Generator) Buses, and 9 PQ (Load) Buses.

2.1. Bus Data Entry

The bus data provided in the system specifications was entered into the MATPOWER case file using the matrix format.

- **Bus 1 (Slack):** The voltage is specified as 1.06 p.u., and the angle is 0 degrees. In MATPOWER, it is coded as Type 3, with the voltage magnitude being constant.
- **Buses 2, 3, 6, and 8 (PV):** Defined as voltage-controlled buses and coded as Type 2. Bus 2 is set with 40 MW generation and a 1.045 p.u. voltage setpoint, while Buses 3, 6, and 8 serve as synchronous condensers with their respective voltage setpoints.
- **Buses 4, 5, 7, 9, 10, 11, 12, 13, and 14 (PQ):** Load data (MW and MVAr) were entered into the respective columns, and these buses were defined as Type 1 (Load Buses).

```
%% Bus Veri Bilgileri

% (Bus_no, bus_tipi, Pd, Qd, Gs, Bs, Area, Vm, Va, BasekV, Zone, Vmax, Vmin)

mpc.bus =[
    1  3 0.0  0.0  0.0 0.0  1 1.060  0.00  0 1 1.06 0.94;
    2  2 21.7 12.7 0.0 0.0  1 1.045 -4.98  0 1 1.06 0.94;
    3  2 94.2 19.0 0.0 0.0  1 1.010 -12.72 0 1 1.06 0.94;
    4  1 47.8 -3.9 0.0 0.0  1 1.019 -10.33 0 1 1.06 0.94;
    5  1 7.6  1.6  0.0 0.0  1 1.020 -8.78  0 1 1.06 0.94;
    6  2 11.2 7.5  0.0 0.0  1 1.070 -14.22 0 1 1.06 0.94;
    7  1 0.0  0.0  0.0 0.0  1 1.062 -13.37 0 1 1.06 0.94;
    8  2 0.0  0.0  0.0 0.0  1 1.090 -13.36 0 1 1.06 0.94;
    9  1 29.5 16.6 0.0 19.0 1 1.056 -14.94 0 1 1.06 0.94;
    10 1 9.0  5.8  0.0 0.0  1 1.051 -15.10 0 1 1.06 0.94;
    11 1 3.5  1.8  0.0 0.0  1 1.057 -14.79 0 1 1.06 0.94;
    12 1 6.1  1.6  0.0 0.0  1 1.055 -15.07 0 1 1.06 0.94;
    13 1 13.5 5.8  0.0 0.0  1 1.050 -15.16 0 1 1.06 0.94;
    14 1 14.9 5.0  0.0 0.0  1 1.036 -16.04 0 1 1.06 0.94;
];

%% Jeneratör Bilgileri

% (Bus_no, Pg, Qg, Qmax, Qmin, Vg, MVA_base, Status, Pmax, Pmin)

mpc.gen = [
    1 232.4 -16.9 999   -999    1.060   100 1   999 0   0   0   0   0;
    2 40.0   42.4 50.0  -40.0   1.045   100 1   140 0   0   0   0   0;
    3 0.0    23.4 40.0   0.0    1.010   100 1   100 0   0   0   0   0;
    6 0.0    12.2 24.0  -6.0    1.070   100 1   100 0   0   0   0   0;
    8 0.0    17.4 24.0  -6.0    1.090   100 1   100 0   0   0   0   0;
];
```

Figure 2: Defining Bus Data in the System

2.2. Line Data Entry

The 20 transmission lines in the system were modeled using the provided impedance (R+jX) and line charging capacitance values. The line charging values were added to the B (Susceptance) column of MATPOWER's branch matrix, consistent with the Pi-Equivalent circuit model.

```
%% Hat Bilgileri

% (From_Bus, To_Bus, R, X, B, Tap, Shift, RateA , RateB, RateC, Status, AngMin, AngMax)

mpc.branch = [
    1   2   0.01938 0.05917 0.0528      0   0   0   0   0   1   -360    360;
    1   5   0.05403 0.22304 0.0492      0   0   0   0   0   1   -360    360;
    2   3   0.04699 0.19797 0.0438      0   0   0   0   0   1   -360    360;
    2   4   0.05811 0.17632 0.0340      0   0   0   0   0   1   -360    360;
    2   5   0.05695 0.17388 0.0346      0   0   0   0   0   1   -360    360;
    3   4   0.06701 0.17103 0.0128      0   0   0   0   0   1   -360    360;
    4   5   0.01335 0.04211 0.0         0   0   0   0   0   1   -360    360;
    4   7   0.0 0.20912 0.0             0   0   0   0.978   0   1   -360    360;
    4   9   0.0 0.55618 0.0             0   0   0   0.969   0   1   -360    360;
    5   6   0.0 0.25202 0.0             0   0   0   0.932   0   1   -360    360;
    6   11  0.09498 0.19890 0.0         0   0   0   0   0   1   -360    360;
    6   12  0.12291 0.25581 0.0         0   0   0   0   0   1   -360    360;
    6   13  0.06615 0.13027 0.0         0   0   0   0   0   1   -360    360;
    7   8   0.0 0.17615 0.0             0   0   0   0   0   1   -360    360;
    7   9   0.0 0.11001 0.0             0   0   0   0   0   1   -360    360;
    9   10  0.03181 0.08450 0.0         0   0   0   0   0   1   -360    360;
    9   14  0.12711 0.27038 0.0         0   0   0   0   0   1   -360    360;
    10  11  0.08205 0.19207 0.0         0   0   0   0   0   1   -360    360;
    12  13  0.22092 0.19988 0.0         0   0   0   0   0   1   -360    360;
    13  14  0.17093 0.34802 0.0         0   0   0   0   0   1   -360    360;

];
```

Figure 3: Defining Line Data in the System

3. Result and Analysis

The power flow results obtained upon executing the developed algorithm are presented below. The analysis successfully converged into four iterations, showing that the system is operating at a stable point and the initial guesses were appropriate.

3.1. Bus Admittance Matrix (Y-Bus) and Bus Results

The screen output below displays the system's bus analysis results, including voltage magnitudes and angles. Due to its enormous size (14x14), the complex admittance matrix (Y-Bus) is provided in Appendix A.

Newton's method power flow (power balance, polar) converged in 4 iterations.

2. COMPREHENSIVE BUS ANALYSIS RESULTS (4 Iterations)

Bus No	Bus Type	Voltage (p.u.)	Angle (Deg)	Generator Output P (MW)	Generator Output Q (MVAr)	Load Status P (MW)	Load Status Q (MVAr)
1	Slack	1.0600	0.0000	232.3933	-16.5493	0.0000	0.0000
2	PV	1.0450	-4.9826	40.0000	43.5571	21.7000	12.7000
3	PV	1.0100	-12.7251	-0.0000	25.0753	94.2000	19.0000
4	PQ	1.0177	-10.3129	0.0000	0.0000	47.8000	-3.9000
5	PQ	1.0195	-8.7739	-0.0000	0.0000	7.6000	1.6000
6	PV	1.0700	-14.2209	-0.0000	12.7309	11.2000	7.5000
7	PQ	1.0615	-13.3596	0.0000	-0.0000	0.0000	0.0000
8	PV	1.0900	-13.3596	0.0000	17.6235	0.0000	0.0000
9	PQ	1.0559	-14.9385	0.0000	-0.0000	29.5000	16.6000
10	PQ	1.0510	-15.0973	0.0000	0.0000	9.0000	5.8000
11	PQ	1.0569	-14.7906	0.0000	-0.0000	3.5000	1.8000
12	PQ	1.0552	-15.0756	0.0000	-0.0000	6.1000	1.6000
13	PQ	1.0504	-15.1563	0.0000	-0.0000	13.5000	5.8000
14	PQ	1.0355	-16.0336	0.0000	0.0000	14.9000	5.0000
TOTAL				272.3933	82.4375	259.0000	73.5000

Figure 4: Busbar Analysis Results

Figure 4 above summarizes the active and reactive power flows across the twenty transmission lines, as well as the losses associated with each branch.

Analysis:

- **Voltage Profile:** The minimum system voltage was observed at Bus 3 as 1.0100 pu Since this value remains within the accepted limits for power systems (0.95 – 1.05 p.u.), the system voltage profile is considered healthy and stable.

- **Slack Bus (Bus 1):** To balance the total system loads and transmission losses, the Slack bus generates 232.40 MW of active power and absorbs 16.55 MVAr of reactive power.

- **PV Bus (Bus 2):** To keep the voltage at the specified set point of 1.045 pu, this generator injects 43.56 MVAr of reactive power into the grid (operating in an over-excited mode).

3.2. Line Flows and Losses

The power flows at both ends of the transmission lines and the (I^2 * R and I^2 * X) losses occurring in the lines are detailed below.

3. LINE FLOWS AND LOSSES

Line	Path Flow	FROM BUS Injection		TO BUS Injection		LOSSES	
No	From->To	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1 -> 2	156.8829	-20.4043	-152.5853	27.6762	4.2976	7.2720
2	1 -> 5	75.5104	3.8550	-72.7475	2.2294	2.7629	6.0843
3	2 -> 3	73.2376	3.5602	-70.9143	1.6022	2.3233	5.1624
4	2 -> 4	56.1315	-1.5504	-54.4548	3.0207	1.6767	1.4703
5	2 -> 5	41.5162	1.1710	-40.6125	-2.0990	0.9038	-0.9280
6	3 -> 4	-23.2857	4.4731	23.6591	-4.8357	0.3734	-0.3625
7	4 -> 5	-61.1582	15.8236	61.6727	-14.2010	0.5144	1.6226
8	4 -> 7	28.0742	-9.6811	-28.0742	11.3843	-0.0000	1.7032
9	4 -> 9	16.0798	-0.4276	-16.0798	1.7323	-0.0000	1.3047
10	5 -> 6	44.0873	12.4707	-44.0873	-8.0495	0.0000	4.4212
11	6 -> 11	7.3533	3.5605	-7.2979	-3.4445	0.0554	0.1160
12	6 -> 12	7.7861	2.5034	-7.7143	-2.3540	0.0718	0.1495
13	6 -> 13	17.7480	7.2166	-17.5359	-6.7989	0.2121	0.4177
14	7 -> 8	-0.0000	-17.1630	0.0000	17.6235	0.0000	0.4605
15	7 -> 9	28.0742	5.7787	-28.0742	-4.9766	0.0000	0.8021
16	9 -> 10	5.2276	4.2191	-5.2147	-4.1849	0.0129	0.0342
17	9 -> 14	9.4264	3.6100	-9.3102	-3.3629	0.1162	0.2471
18	10 -> 11	-3.7853	-1.6151	3.7979	1.6445	0.0126	0.0295
19	12 -> 13	1.6143	0.7540	-1.6080	-0.7483	0.0063	0.0057
20	13 -> 14	5.6439	1.7472	-5.5898	-1.6371	0.0541	0.1101
TOTAL LOSSES						13.3933	30.1224

Figure 5: Line Flows and Losses

Analysis:

- **System Losses:** The total active power loss in the transmission network was calculated as 13.40 MW. This is approximately 4.9% of the total generation, indicating an efficient transmission system. However, the total reactive power loss was seen to be 30.12 MVAr, which is significant and highlights the reactive power consumption of the line inductances under the current loading conditions.
- **Critical Line Flows:** The highest power transfer was seen on Line 1-2, with an active power flow of 156.89 MW leaving the Slack Bus. This line also accounted for the highest individual active power loss of 4.30 MW due to the high current magnitude.
- **Secondary Flows**: Line 1-5 and Line 2-3 also carry significant loads (75.51 MW and 73.24 MW, respectively), acting as the main backbone for distributing power from the generation centers to the load buses.
- **Reactive Power Flow (Line 7-8):** It is worth noting that Line 7-8 carries negligible active power (0.00 MW) but a significant reactive power flow of 17.16 MVAr. This confirms that the generator at Bus 8 is operating purely as a synchronous condenser, providing voltage support to the network without supplying active power.

APPENDICES

APPENDIX A: Bus Admittance Matrix (Y- Bus)

Due to the large dimensions of the IEEE 14-Bus system (14 x 14), the complex admittance matrix is presented in two parts for readability.

Bus	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7
1	**6.025 - j19.447**	**-4.999 + j15.263**	**0**	**0**	**-1.026 + j4.235**	**0**	**0**
2	**-4.999 + j15.263**	**9.521 - j30.272**	**-1.135 + j4.782**	**-1.686 + j5.116**	**-1.701 + j5.194**	**0**	**0**
3	**0**	**-1.135 + j4.782**	**3.121 - j9.822**	**-1.986 + j5.069**	**0**	**0**	**0**
4	**0**	**-1.686 + j5.116**	**-1.986 + j5.069**	**10.513 - j38.654**	**-6.841 + j21.579**	**0**	**0**
5	**-1.026 + j4.235**	**-1.701 + j5.194**	**0**	**-6.841 + j21.579**	**9.568 - j35.534**	**0 + j4.257**	**0**
6	**0**	**0**	**0**	**0**	**0 + j4.257**	**6.580 - j17.341**	**0**
7	**0**	**0**	**0**	**0 + j4.890**	**0**	**0**	**0 - j19.549**
8	**0**	**0**	**0**	**0**	**0**	**0**	**0 + j5.677**
9	**0**	**0**	**0**	**0 + j1.855**	**0**	**0**	**0 + j9.090**
10	**0**	**0**	**0**	**0**	**0**	**0**	**0**
11	**0**	**0**	**0**	**0**	**0**	**-1.955 + j4.094**	**0**
12	**0**	**0**	**0**	**0**	**0**	**-1.526 + j3.176**	**0**
13	**0**	**0**	**0**	**0**	**0**	**-3.099 + j6.103**	**0**
14	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Table A.1: Y-Bus Matrix (Columns 1 - 7)

Bus	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13	Bus 14
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0 + j1.855	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	-1.955 + j4.094	-1.526 + j3.176	-3.099 + j6.103	0
7	0 + j5.677	0 + j9.090	0	0	0	0	0
8	0 - j5.677	0	0	0	0	0	0
9	0	5.326 - j24.093	-3.902 + j10.365	0	0	0	-1.424 + j3.029
10	0	-3.902 + j10.365	5.783 - j14.768	-1.881 + j4.403	0	0	0
11	0	0	-1.881 + j4.403	3.836 - j8.497	0	0	0
12	0	0	0	0	4.015 - j5.428	-2.489 + j2.252	0
13	0	0	0	0	-2.489 + j2.252	6.725 - j10.670	-1.137 + j2.315
14	0	-1.424 + j3.029	0	0	0	-1.137 + j2.315	2.561 - j5.344

Table A.2: Y-Bus Matrix (Columns 8 - 14)