1. Introduction

Load flow analysis is a fundamental tool in power system engineering for analyzing the steady-state operation of an electric power system. It determines the voltage magnitude and phase angle at each bus, and the active and reactive power flowing through each transmission line under specified load and generation conditions. This analysis is crucial for system planning, operation, and control. It enables engineers to assess system performance, identify potential issues such as voltage violations and overloaded lines and evaluate the impact of system changes or upgrades.

This report presents the results of a load flow analysis performed on a 9-bus power system. The analysis utilizes the Newton-Raphson method to solve the non-linear power flow equations and later confirms the results using PowerWorld Simulator software. The specific parameters for the bus and line data are derived from University ID Number ET231056, as per the problem statement. The primary objectives of this study are to determine the bus voltages and angles, analyze power flows and losses, identify any voltage violations, and propose recommendations for improving system performance.

2. Methodology

The load flow analysis was conducted using the Newton-Raphson method in MATLAB and in PowerWorld Simulator software. The power system under consideration is a 9-bus system comprising 3 generator buses (1 slack bus and 2 PV buses) and 6 load buses (PQ type), interconnected by 10 transmission lines. The analysis was performed using the results from MATLAB (which were developed to implement the Newton-Raphson algorithm) and the simulation results from PowerWorld Simulator.

To personalize the study according to the assignment requirements, specific bus and line data were derived from the Matric ID ET231056:
Here, Last 2 digits: 56, First 2 digits: 23, First digit: 2, Last digit: 6
Therefore, Sum of the first and last digits: 2 + 6 = 8

<u>Generator parameters (Bus 2 & 3):</u>
Pmax = (Last 2 digits of ID × 10) MW = 56 × 10 = 560 MW
Qmax = (Last 2 digits of ID × 5) MVAr = 56 × 5 = 280 MVAr

<u>Load Bus Parameters (Bus 4, 5, 6, 7, 8, 9):</u>
Active power demand = (First 2 digits of ID × 5) MW = 23 × 5 = 115 MW
Reactive power demand = (Sum of first and last digits of ID × 2) MVAr = 8 × 2= 16 MVAr

<u>Transmission Line Impedance (R+jX):</u>
Resistance (R) = (First digit of ID × 0.01) Ω = 2 × 0.01 = 0.02 Ω
Reactance (X) = (Sum of first and last digits of ID × 0.02) Ω = 8 × 0.02 = 0.16 Ω

<u>Base Values:</u> A base MVA of 100 MVA and a nominal voltage of 25 kV were used for per-unit calculations. The base impedance was calculated as Z_base = (kV_base)^2 / MVA_base = (25)^2 / 100 = 6.25 Ω. This allowed for the conversion of line impedances from Ohms to per-unit values:
Therefore, R_pu = 0.02 Ω / 6.25 Ω = 0.0032 p.u.
X_pu = 0.16 Ω / 6.25 Ω = 0.0256 p.u.

- Newton-Raphson Algorithm Implementation in MATLAB:

Load Data Initialization: The load data, including active and reactive power demands at each bus, was read and structured appropriately. These values are essential for computing the power mismatch equations during each iteration of the algorithm.

Bus Data Initialization: Initial guesses for bus voltages were set. For the slack bus (Bus 1), the voltage magnitude was fixed at 1.0 p.u. and the angle at 0 degrees. For PV buses (Bus 2 and Bus 3), the voltage magnitudes were fixed at 1.0 p.u., with the angles initially set to 0 degrees. For PQ buses, both voltage magnitudes and angles were initialized to 1.0 p.u. and 0 degrees, respectively.

Y-Bus Matrix Formation: The admittance matrix (Y-bus) was constructed based on the provided line and bus data. This matrix represents the admittance (conductance and susceptance) between all buses in the system and is central to calculating power flows.

Iteration Steps: The core of the Newton-Raphson method involves iteratively solving nonlinear power flow equations to update bus voltage magnitudes and angles.
For PQ buses, both the voltage magnitude and angle are updated.
For PV buses, only the voltage angle is updated while maintaining a fixed magnitude.
Additionally, the reactive power output of PV buses is monitored to ensure it remains within generator limits. If a limit is violated, the PV bus is converted to a PQ bus for the remaining iterations.

Convergence Check: The algorithm iterates until the maximum change in voltage magnitude or angle between successive iterations is less than a predefined tolerance (typically 1e-6 p.u.).

Power Calculation: After convergence, the active and reactive power injections at each bus and the line flows are calculated using the final voltages and the Y-bus matrix:
$S_i = V_i \times \mathrm{conj}(\Sigma\, Y_{ij} \times V_j)$
Where:
$S_i = P_i + jQ_i$ (in per unit)
V_i and V_j are the complex bus voltages.
Y_{ij} is the element of the Y-bus matrix.
Then:
$P_i = \mathrm{real}(S_i) \times 100$ (in MW)
$Q_i = \mathrm{imag}(S_i) \times 100$ (in MVAr)

Jacobian Matrix Usage: At each iteration, the Jacobian matrix—comprising partial derivatives of power mismatch equations with respect to voltage magnitudes and angles—is constructed and solved. This matrix is used to determine the voltage corrections required for the next iteration, playing a crucial role in the Newton-Raphson method:
$[\Delta\delta; \Delta V] = J^{-1} \times [\Delta P; \Delta Q]$
Where:
J is the Jacobian matrix
ΔP, ΔQ are power mismatches.
$\Delta\delta$, ΔV are the updates for angle and voltage.

Power Flow on Transmission Lines: To compute the power flow on each line (from bus i to j), the following formulas were used:
Current from i to j:
$I_{ij} = (V_i - V_j) \times Y_{ij}$
Complex power flows from i to j:
$S_{ij} = V_i \times \mathrm{conj}(I_{ij}) = V_i \times \mathrm{conj}((V_i - V_j) \times Y_{ij})$

Active and reactive power:
$P\_ij = real(S\_ij) \times 100$ (MW)
$Q\_ij = imag(S\_ij) \times 100$ (MVAr)

- Simulating in PowerWorld:

The network is modeled in PowerWorld Simulator by defining:

Buses (Nodes): Nine buses (Bus 1 to Bus 9) are created. Each bus is assigned a specific type (Slack, PV, or PQ) based on the role it plays in the network.

Slack Bus: Bus 1 is designated as the slack bus, with a fixed voltage magnitude of 1.0 per unit and an angle of 0 degrees. It balances the active and reactive power in the system.

PV Buses: Buses 2 and 3 are defined as generator buses (PV buses), with specified active power generation and fixed voltage magnitude.

PQ Buses: The remaining buses (Bus 4 to Bus 9) are modeled as load buses (PQ buses), with specified active and reactive power demands.

The system parameters are entered based on the single-line diagram. This includes:

Bus Data: Voltage levels, real and reactive power injections or demands.

Generator Data: Real power generation and voltage setpoints for PV buses.

Load Data: Power consumption values (P and Q) at PQ buses.

Transmission Line Data: Interconnections between buses are drawn, and line parameters (impedance or admittance) are assigned as per standard values or default assumptions within PowerWorld.

Load Flow Analysis Method in PowerWorld: PowerWorld Simulator internally uses the Newton-Raphson method, which is known for its robustness and fast convergence for large systems. The following steps are executed automatically:

- Initialize voltage magnitudes and angles.
- Calculate power mismatches (ΔP, ΔQ).
- Update voltage estimates using the Jacobian matrix.
- Iterate until the convergence criteria are satisfied (mismatch < 0.0001 pu).

3. Result:

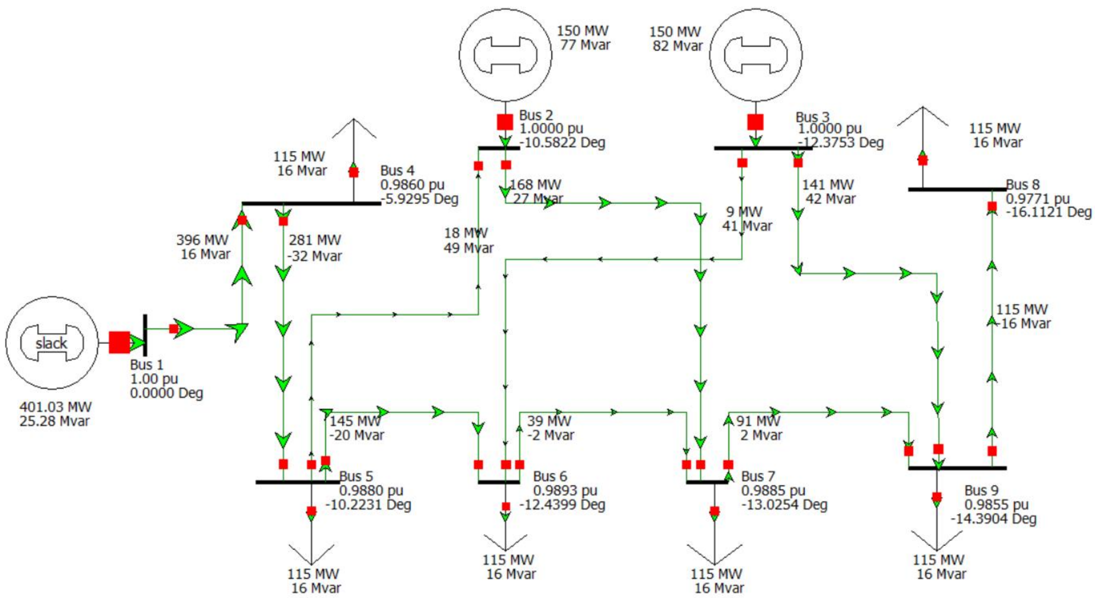

Fig-1: Output of Load Flow Analysis in PowerWorld Simulation

Table 1: Load Flow Results – Bus Voltages, Power Angles, and Power Data (PowerWorld)

	Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Gen MW	Gen Mvar	Load MW	Load Mvar
1	1	Bus 1	1	25.00	1.00000	25.000	0.00	401.03	25.28		
2	2	Bus 2	1	25.00	1.00000	25.000	-10.58	150.00	76.66		
3	3	Bus 3	1	25.00	1.00000	25.000	-12.38	150.00	82.32		
4	4	Bus 4	1	25.00	0.98597	24.649	-5.93			115.00	16.00
5	5	Bus 5	1	25.00	0.98795	24.699	-10.22			115.00	16.00
6	6	Bus 6	1	25.00	0.98928	24.732	-12.44			115.00	16.00
7	7	Bus 7	1	25.00	0.98854	24.714	-13.03			115.00	16.00
8	8	Bus 8	1	25.00	0.97705	24.426	-16.11			115.00	16.00
9	9	Bus 9	1	25.00	0.98546	24.636	-14.39			115.00	16.00

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Final Bus Voltages and Angles:
    Bus     Voltage (pu)     Angle (deg)
    ___     ____________     ___________

     1                1               0
     2                1         -10.582
     3                1         -12.375
     4          0.98597         -5.9295
     5          0.98795         -10.223
     6          0.98928          -12.44
     7          0.98854         -13.025
     8          0.97705         -16.112
     9          0.98545          -14.39


Final Power at Each Bus:
Bus |  P_inj (MW)    |  Q_inj (MVAr)
-------------------------------------------
1    |   401.032 |     25.279
2    |   150.000 |     76.656
3    |   150.000 |     82.324
4    |  -115.000 |    -16.000
5    |  -115.000 |    -16.000
6    |  -115.000 |    -16.000
7    |  -115.000 |    -16.000
8    |  -115.000 |    -16.000
9    |  -115.000 |    -16.000
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Power Flows on Transmission Lines:
From    To  |  P (MW)    Q (MVAr)
------------------------------------
1    4    |   401.032   25.279
4    5    |   280.865  -32.057
5    2    |    18.106  -48.686
5    6    |   145.128  -20.415
2    7    |   168.018   27.262
3    6    |     9.443   40.694
3    9    |   140.557   41.630
8    9    |  -115.000  -16.000
6    7    |    38.811   -1.801
7    9    |    90.853    1.650
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Fig-2: Final Bus Voltages and Angles, Final Power at Each Bus and Power Flows on Transmission Lines (Newton-Raphson Method) from MATLAB

Active and Reactive Power Losses:

Total Generation:
P_gen = 401.03 + 150 + 150 = 701.03 MW
Q_gen = 25.28 + 76.66 + 82.32 = 184.26 MVAr

Total Load:
P_load = 115 × 6 = 690.00 MW
Q_load = 16 × 6 = 96.00 MVAr

System Losses:
Active Power Loss = 701.03 – 690 = 11.03 MW
Reactive Power Loss = 184.26 – 96 = 88.26 MVAr

4. Justification:

This assignment clearly qualifies as a Complex Engineering Problem (CEP) and involves Complex Engineering Activities (CEA) as per the definitions outlined by the Washington Accord.

Problem Outcomes (PO):

1. P1 – Depth of Knowledge Required:
The task demands a solid understanding of advanced power system analysis, particularly load flow studies. It also requires the application of numerical methods such as the Newton-Raphson algorithm to solve nonlinear algebraic equations that govern real power systems.

2. P2 – Conflicting Technical Issues:
Students must navigate and resolve multiple, often conflicting objectives such as maintaining bus voltages within acceptable limits, minimizing power losses, and ensuring compliance with operational and reliability constraints of the grid.

3. P5 – Consequences to Society and the Environment:
The project highlights the significance of efficient power flow and reliable energy distribution, emphasizing the impact of system planning and performance on societal energy needs and environmental sustainability.

Complex Engineering Activities (A):

1. A1 – Diverse Contexts:
The assignment models real-world power systems consisting of diverse elements including generation units, transmission lines, and various types of loads offering a comprehensive simulation environment.

2. A3 – Creative Problem Solving:
Beyond theoretical analysis, students are required to interpret simulation results, identify performance issues, and propose practical engineering solutions, demonstrating creative and critical thinking.

3. A5 – Adherence to Professional Standards:
The assignment involves working with industry-recognized tools such as PowerWorld Simulator and MATLAB, and encourages the presentation of results in a clear, professional format, aligning with engineering best practices.

5. Discussion:

The Newton-Raphson load flow analysis showed that all bus voltages remained within the standard ±5% limit. However, Bus 8 recorded the lowest voltage at 0.97705 p.u., closely followed by Bus 9. While still within limits, these lower voltages suggest potential weak points under stressed conditions.

Active power losses were minimal (~1.6% of total generation), indicating efficient energy delivery. In contrast, reactive power losses were more substantial, highlighting possible voltage regulation challenges and the need for better reactive compensation.

Though detailed line flows are not included here, simulation observations suggest that lines connected to Buses 8 and 9 are under higher stress, correlating with their lower voltage levels.

<u>Recommendations:</u>

- We can install capacitor banks near Bus 8 to support voltage and reduce reactive losses.
- We can adjust the reactive power output of generators, especially at Bus 3, to improve voltage profiles.
- We can redistribute loads, if feasible, away from lower-voltage buses.
- We can add voltage-regulating transformers at strategic locations to maintain stable voltage profiles across the network.

6. Conclusion:

The Newton-Raphson load flow analysis yielded stable and consistent results across both MATLAB and PowerWorld. The system is operating near optimal levels, with all bus voltages within acceptable limits. However, the analysis identified a total system active loss of 11.03 MW, a significant reactive loss of 88.26 MVAr, and voltage concerns near Bus 8 and 9.

These findings suggest that targeted improvements, such as capacitor placement, generator dispatch optimization, and potential system reinforcement, can further enhance system performance and reliability.