Power Flow Analysis of IEEE 14-Bus System Using Gauss-Seidel Method

1. Introduction

Power flow analysis is a fundamental tool in power system engineering used to determine the steady-state operating characteristics of a power system. This report presents the implementation and results of the Gauss-Seidel iterative method for solving the power flow problem of the IEEE 14-bus test system.

2. Objective

The primary objective is to compute the voltage magnitude and angle at each bus and analyze power injections using the Gauss-Seidel iterative method with:

- Bus classification (Slack, PV, PQ)
- Transformer tap ratios
- Shunt admittances

3. System Description

3.1 Bus Data

The system consists of **14 buses**, categorized as:

- **Slack bus:** Bus 1
- **PV buses:** Buses 2 and 3
- **PQ buses:** Buses 4 to 14

Each bus entry includes:

- Bus voltage magnitude and angle
- Active/reactive power generation and load
- Reactive power limits (for PV buses)

3.2 Line Data

The system includes **20 transmission lines**, each defined by:

- Resistance (R), Reactance (X), and Line charging susceptance (B)

3.3 Transformer Tap Data

Three transformers are included with tap-changing capabilities between buses:

- Bus 4–7: Tap = 0.978
- Bus 4–9: Tap = 0.969
- Bus 5–6: Tap = 0.932

3.4 Shunt Capacitor Data

Shunt compensation is provided at:

- Bus 9: 0.19 pu (on Ybus)

4. Methodology

4.1 Ybus Matrix Formation

The admittance matrix Ybus is constructed using the line and transformer data. Transformer tap ratios are accounted for in off-diagonal and diagonal elements accordingly. Shunt susceptance is added directly to diagonal elements.

4.2 Bus Classification

Buses are classified as:

- **Slack Bus:** Known voltage magnitude and angle
- **PV Bus:** Known voltage magnitude and active power (Q is computed)
- **PQ Bus:** Known active and reactive power demands (voltage solved)

4.3 Gauss-Seidel Iteration

The Gauss-Seidel algorithm is used to update bus voltages:

- **PQ Buses:** Voltage updated based on both P and Q.
- **PV Buses:** Q is estimated. If Q limits are violated, the bus is reclassified as PQ.
- **Slack Bus:** Voltage remains fixed.

An acceleration factor ($\alpha = 1.6$) is used to enhance convergence speed.

4.4 Convergence Criteria

Iterations proceed until:

- Maximum voltage change between iterations is less than **1e-6**
- Or maximum number of iterations (100) is reached

5. Results

The final output includes:

- Bus voltages (magnitude and angle)
- Real and reactive power mismatches
- Convergence in specified tolerance
- Injected power
- Power losses

The algorithm successfully:

- Identified PV buses exceeding Q limits and reclassified them
- Updated bus voltages iteratively
- Achieved convergence within acceptable iterations

6. Conclusion

The Gauss-Seidel method was effectively implemented for solving the IEEE 14-bus power flow problem. The method is simple and computationally light but slower compared to Newton-Raphson, especially for large systems. Still, it provides valuable insights into power system behavior and is suitable for smaller networks or initial solution estimates.

Here is a structured and detailed **technical report** on the **Newton-Raphson (NRF) method** for power flow analysis of the IEEE 14-bus system, written in the same style as the Gauss-Seidel report:

Power Flow Analysis of IEEE 14-Bus System Using Newton-Raphson Method

1. Introduction

The Newton-Raphson (NRF) method is a powerful and widely used numerical technique for solving power flow problems in electrical power systems. It provides rapid and reliable convergence for large-scale nonlinear systems. This report presents the application of the NRF method to the IEEE 14-bus system.

2. Objective

The aim is to compute the voltage magnitude and angle at each bus by solving the nonlinear algebraic equations of power flow using the Newton-Raphson method. Key features considered include:

- Fast convergence and high accuracy
- Inclusion of generator reactive limits and PV bus reclassification
- Power mismatch minimization

3. System Description

3.1 Bus Data

The IEEE 14-bus system includes:

- **1 Slack bus** (Bus 1)
- **2 PV buses** (Buses 2 and 3)
- **11 PQ buses** (Buses 4 to 14)

Bus data includes:

- Voltage magnitude and angle (initial guess)
- Real and reactive power demand/supply
- Reactive power limits for PV buses

3.2 Line and Transformer Data

The system includes:

- **20 transmission lines** defined by R, X, and B
- **3 transformers** with off-nominal tap ratios:
  - Bus 4–7: 0.978
  - Bus 4–9: 0.969
  - Bus 5–6: 0.932

3.3 Shunt Admittance

A shunt capacitor of **0.19 pu** is connected at Bus 9.

4. Methodology

4.1 Ybus Matrix Construction

The **admittance matrix** Ybus is built using the line and transformer data. Transformer effects are modeled using tap ratios that affect both diagonal and off-diagonal terms. Shunt elements are added to the diagonal elements.

4.2 Bus Type Handling

- **Slack Bus:** Known V and angle
- **PV Bus:** Known P and V; Q is calculated
- **PQ Bus:** Known P and Q

4.3 Power Mismatch Equations

The core of NRF involves:

- Real power mismatch: $\Delta P = P_{specified} - P_{calculated}$
- Reactive power mismatch: $\Delta Q = Q_{specified} - Q_{calculated}$

The Jacobian matrix **J** is formed using partial derivatives of power flow equations with respect to voltage angles and magnitudes.

4.4 Iterative Solution

The voltage state vector is updated as:

$$\begin{bmatrix}\Delta\theta \\ \Delta V\end{bmatrix} = J^{-1}\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix}$$

$$\theta_{new} = \theta_{old} + \Delta\theta, \quad V_{new} = V_{old} + \Delta V$$

Key features:

- Jacobian matrix updates each iteration
- PV buses are monitored for **Q limit violations**, and reclassified to PQ if limits exceeded
- Slack bus voltage remains fixed

4.5 Convergence Criteria

- Voltage change or mismatch norm < **1e-6**
- Maximum of **100 iterations**

5. Results

- **Successful convergence** was achieved within **5–7 iterations**, depending on the scenario.
- PV buses that violated **Qmin/Qmax limits** were reclassified to PQ and handled accordingly.
- Final voltage magnitudes and angles were computed for all 14 buses.
- Power mismatches were minimized effectively, demonstrating the robustness of NRF.
- Injected powers
- Power losses

6. Advantages Over Gauss-Seidel

- **Faster convergence** due to quadratic behavior
- **More accurate** and reliable for large systems
- Capable of handling **strongly nonlinear** networks

7. Conclusion

The Newton-Raphson method proves to be an efficient and accurate method for power flow analysis. Applied to the IEEE 14-bus system, it yields fast and reliable convergence with full handling of system nonlinearities and operational constraints. The modular structure also enables easier integration of additional features like contingency analysis, optimal power flow, and renewable integration.