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Load Flow Study of a 69-Bus Radial Distribution Network with Optimal Reactive Power Compensation

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Abstract: This paper presents a load flow analysis of a 69-bus radial distribution system using MATLAB programming. Reactive power compensation is implemented through switched shunt capacitors to improve the voltage profile and system performance. The proposed approach determines suitable capacitor placement for effective reactive power injection at selected load buses. The developed MATLAB program calculates voltage magnitude and angle at each bus and identifies buses operating outside permissible voltage limits. Simulation results show that the installation of switched shunt capacitors significantly improves voltage regulation and brings the bus voltages within the specified range. The method is effective for enhancing voltage stability and maintaining a near-flat voltage profile in radial distribution networks.

Keywords: Radial distribution network, 69-bus test system, forward–backward sweep method, Reactive power injection, Voltage stability, Capacitor placement, MATLAB.

I. INTRODUCTION

Distribution systems represent the final stage in electric power delivery and are responsible for supplying electricity to end users. These systems are generally radial in configuration, characterized by a single power source and sequential power flow from the substation to downstream buses. Due to their high resistance-to-reactance (R/X) ratio and relatively long feeder lengths, radial distribution networks are more susceptible to voltage variations and power losses compared to transmission systems [1].

One of the major technical challenges in radial distribution systems is voltage drop along the feeder. Every distribution line possesses inherent impedance, expressed as $Z=R+jX$. When load current flows through this impedance, a voltage drop proportional to the line current and impedance is produced. Mathematically, the voltage drop across a feeder section can be approximated as:

$$\Delta V=I(R+jX)$$

As power is delivered to loads along the feeder, the current flowing through upstream sections increases due to cumulative downstream demand. Consequently, the voltage magnitude gradually decreases from the sending end (substation) toward the receiving end (tail bus). In addition, voltage magnitude in distribution systems is highly sensitive to reactive power flow. Increased reactive power demand leads to additional voltage reduction, particularly under heavy loading conditions. Therefore, far-end buses in radial networks often experience the lowest voltage levels.

Voltage deviation significantly affects the performance of connected electrical equipment. Heating loads produce power proportional to the square of the applied voltage, and therefore reduced voltage decreases heat output while increased voltage may cause overheating. Similarly, the torque developed by induction motors is proportional to the square of voltage, and voltage reduction can lead to insufficient starting torque, stalling, and overheating. Transformers subjected to higher voltage operate near saturation, resulting in increased magnetizing current and temperature rise. Lighting loads experience reduced illumination at low voltage and shortened service life at higher voltage. Although many electronic devices can tolerate moderate voltage variations, excessive deviation may still lead to malfunction or reduced lifespan. These effects highlight the necessity of maintaining bus voltages within the permissible limit of ±5% of nominal value [2].

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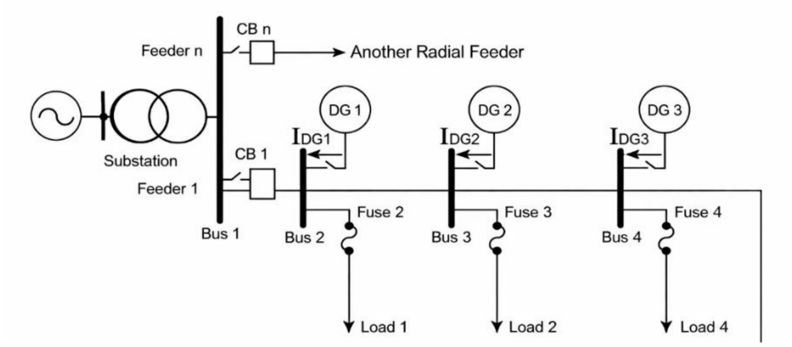

Fig. 1. Single-line diagram of a radial distribution feeder integrated with distributed generation and protective devices.

Fig. 1 illustrates a typical radial distribution feeder integrated with distributed generation (DG) units. The system originates from a substation that supplies power through a circuit breaker to the main feeder. The feeder consists of sequential buses supplying loads protected by fuses. Distributed generators are connected at intermediate buses and inject current locally into the system. The integration of DG units modifies the traditional unidirectional power flow, as current may flow in both upstream and downstream directions depending on generation and load conditions. While DG improves voltage profile and reduces feeder current, it also increases fault current levels and complicates protection coordination. The presence of distributed generation changes the voltage profile behavior of the feeder. Local power injection reduces the current drawn from the substation and may improve voltage levels at downstream buses. However, improper coordination of reactive power and protection devices can lead to operational challenges. Therefore, accurate load flow analysis becomes essential to evaluate system performance under different operating conditions.

To accurately analyze voltage behavior in such systems, efficient load flow analysis is required. Conventional load flow methods such as Newton–Raphson and Gauss–Seidel are less suitable for radial distribution systems due to their structural characteristics and high R/X ratio. The forward–backward sweep method is widely adopted for radial networks because of its computational efficiency and compatibility with radial topology [3].

Reactive power compensation is an effective technique for mitigating voltage drop and improving voltage profile. Shunt capacitors are commonly employed in distribution systems due to their simplicity, low cost, and ability to provide local reactive power support [4]. Proper placement and sizing of capacitors significantly enhance voltage regulation and reduce feeder losses.

In this study, load flow analysis of the IEEE 69-bus radial distribution system is performed using the forward–backward sweep method implemented in MATLAB. Switched shunt capacitors are installed at selected buses to inject reactive power and improve voltage regulation. The effectiveness of the proposed method is evaluated in terms of voltage profile enhancement and overall system performance.

II. SYSTEM DESCRIPTION AND LOAD FLOW ANALYSIS

A. IEEE 69-Bus Radial Distribution System

The IEEE 69-bus radial distribution system as shown in fig. 2 is widely used as a standard benchmark network for evaluating load flow algorithms and voltage regulation techniques in distribution systems [6]. The system operates at a base voltage of 12.66 kV and consists of 69 buses and 68 distribution line segments arranged in a radial configuration.

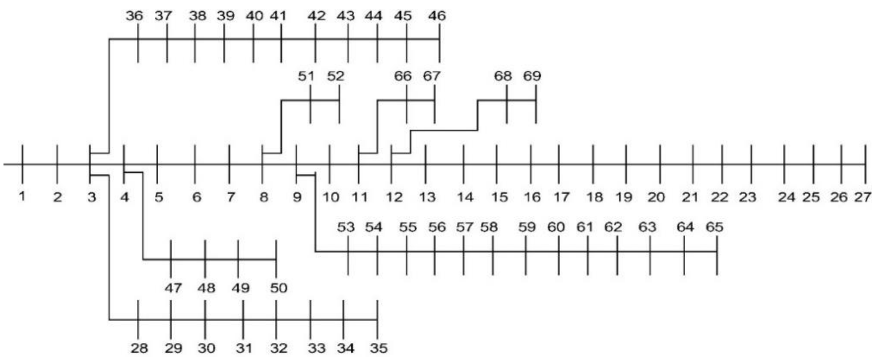

Fig. 2. IEEE 69-bus radial distribution system

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Radial distribution networks are characterized by high resistance-to-reactance (R/X) ratios and long feeder lengths compared to transmission systems [1]. Due to cumulative downstream load demand, feeder current increases toward the sending end, which results in progressive voltage reduction along the feeder. Consequently, the terminal buses generally experience the lowest voltage magnitude, making them critical for voltage stability analysis [3].

All load buses in the system are modeled as constant power (PQ) loads. The system data for line parameters and load demand are adopted from the standard IEEE test feeder specification [6].

B. Mathematical Formulation of Load Flow

The objective of load flow analysis in radial distribution systems is to determine bus voltages, branch currents, and real and reactive power losses.

For a load bus iii, the complex power is given by

$$S_i=P_i+jQ_i$$

The injected current at bus iii can be expressed as [3]:

$$I_i= (P_i-jQ_i)/ V_i^*$$

Where, V_i^* is the complex conjugate of the bus voltage.

For a branch connecting bus i to bus j, the receiving-end voltage is calculated as

$$V_j=V_i-I_{ij}(R_{ij}+jX_{ij})$$

Where, R_{ij} and X_{ij} represent the resistance and reactance of the line section between buses i & j.

Voltage deviation at bus i is defined as

$$\Delta V_i=|V_i-V_{rated}|$$

Maintaining voltage magnitude within ±5% of the nominal value is necessary to ensure proper operation of electrical equipment and system reliability [2].

C. Forward–Backward Sweep Method

Conventional load flow methods such as Newton–Raphson and Gauss–Seidel are not well suited for radial distribution systems due to their high R/X ratio and structural characteristics [3]. The forward–backward sweep method is widely adopted for radial networks because of its computational efficiency and simplicity [3], [7].
The method consists of two main steps:

1) Backward Sweep

Starting from the terminal buses toward the slack bus, branch currents are calculated using

$$I_{branch}=I_{load}+\sum I_{downstream}$$

This step determines the current flowing through each branch of the feeder.

2) Forward Sweep

Beginning from the slack bus and moving toward the terminal buses, bus voltages are updated using

$$V_j=V_i-I_{ij}(R_{ij}+jX_{ij})$$

The backward and forward sweep processes are repeated iteratively until the difference between successive voltage values is less than a predefined tolerance.

The forward–backward sweep method has been shown to provide accurate and stable convergence for radial and weakly meshed distribution systems [3], [7].

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D. Performance Indices

The system performance is evaluated based on:

1. Minimum bus voltage magnitude
2. Voltage profile improvement
3. Voltage deviation reduction
4. Real and reactive power loss assessment

If the bus voltages violate permissible limits, reactive power compensation is required to improve voltage regulation and system stability [4].

III. REACTIVE POWER COMPENSATION USING SHUNT CAPACITORS

A. Need for Reactive Power Compensation

In radial distribution systems, voltage magnitude is highly sensitive to reactive power flow due to the high R/X ratio of distribution lines. An increase in reactive power demand causes additional voltage drop along the feeder, particularly at downstream buses [1], [4]. Therefore, insufficient reactive power support results in poor voltage regulation and increased power losses.

The approximate relationship between voltage change and reactive power flow in a distribution line can be expressed as $\Delta V \approx QX/V$

where Q is the reactive power flow, X is the line reactance, and V is the bus voltage magnitude. This equation indicates that voltage drop is directly proportional to reactive power demand. Hence, local reactive power support is essential to maintain acceptable voltage levels.

Reactive power compensation improves:

1. Voltage profile
2. Power factor
3. System stability
4. Real power loss reduction

Shunt capacitors are commonly used for reactive power compensation in distribution systems due to their simplicity, reliability, and cost-effectiveness [4].

C. Capacitor Placement Strategy

Proper placement of shunt capacitors plays a crucial role in voltage improvement and loss reduction. Capacitors are generally installed at buses where:

1. Voltage magnitude is below the permissible limit
2. Reactive power demand is high
3. Line losses are significant

Several analytical and optimization-based approaches have been proposed for optimal capacitor placement [4], [5]. In this study, buses experiencing maximum voltage deviation are selected for reactive power injection.

IV. SIMULATION RESULTS AND DISCUSSION

A. Base Case Load Flow Results

Load flow analysis of the IEEE 69-bus radial distribution system was carried out using the forward–backward sweep method described in Section II. The simulation was implemented in MATLAB environment.

In the base case (without compensation), the voltage magnitude at downstream buses decreases progressively due to cumulative load demand and feeder impedance. The minimum bus voltage occurs at one of the far-end buses, indicating significant voltage deviation from the nominal value. This behaviour is consistent with the characteristics of radial distribution systems reported in [3].

The voltage profile obtained from the base case clearly shows that several buses operate close to or below the acceptable voltage limit of 0.95 p.u. Such voltage deviation may lead to poor equipment performance and increased system losses as discussed in Section I.

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The total real power loss of the system is calculated using

$$P_{loss}=\sum I_{ij}^2 R_{ij}$$

where I_{ij} is the branch current and R_{ij} is the line resistance between buses i and j.

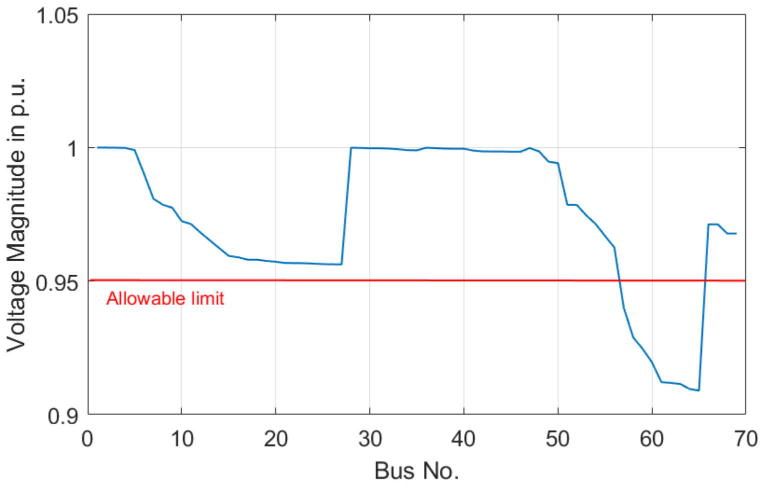

Fig. 3. Voltage profile of IEEE 69-bus system without reactive power compensation.

The voltage profile of the IEEE 69-bus radial distribution system without reactive power compensation is shown in Fig. 3.

From the figure, it is observed that the voltage magnitude gradually decreases as the bus number increases. The minimum voltage occurs at the far-end buses (around buses 60–65), where the voltage drops to approximately 0.91 p.u., which is significantly below the allowable limit of 0.95 p.u.

B. Load Flow with Reactive Power Compensation

To improve the voltage profile, switched shunt capacitors were installed at selected buses exhibiting maximum voltage deviation. The reactive power injected at these buses reduces the reactive power flow from the upstream feeder.

After capacitor placement, load flow analysis was repeated. The results indicate:

1. Increase in minimum bus voltage
2. Reduction in voltage deviation
3. Improvement in overall voltage profile
4. Reduction in real power losses

The voltage magnitude at previously critical buses increases significantly, and all bus voltages are maintained within the permissible range of ±5% of nominal value. This confirms the effectiveness of shunt capacitor compensation in improving voltage regulation [4].

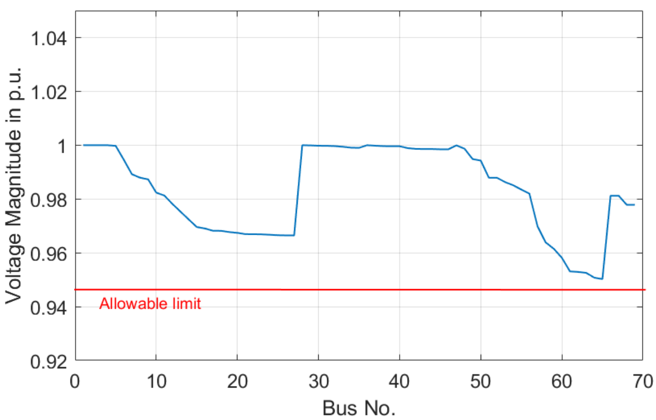

Fig. 4. Voltage profile of IEEE 69-bus system with shunt capacitor compensation.

Fig. 4. shows the voltage profile after installing switched shunt capacitors at selected buses.

It is observed that:

The minimum bus voltage improves to approximately 0.95–0.97 p.u.

All bus voltages remain within the permissible ±5% range.

The voltage curve becomes flatter compared to the uncompensated case.

This improvement occurs because local reactive power injection reduces upstream reactive current flow, thereby minimizing voltage drop along the feeder.

C. Comparison of Voltage Profiles

A comparison between the uncompensated and compensated voltage profiles shows a noticeable improvement after reactive power injection. The voltage curve becomes flatter, indicating improved stability and reduced voltage variation along the feeder.

The improvement can be explained by the reduction in reactive current flowing through upstream branches. Since voltage drop is proportional to line current and impedance, reducing reactive current directly contributes to voltage rise at downstream buses [1].

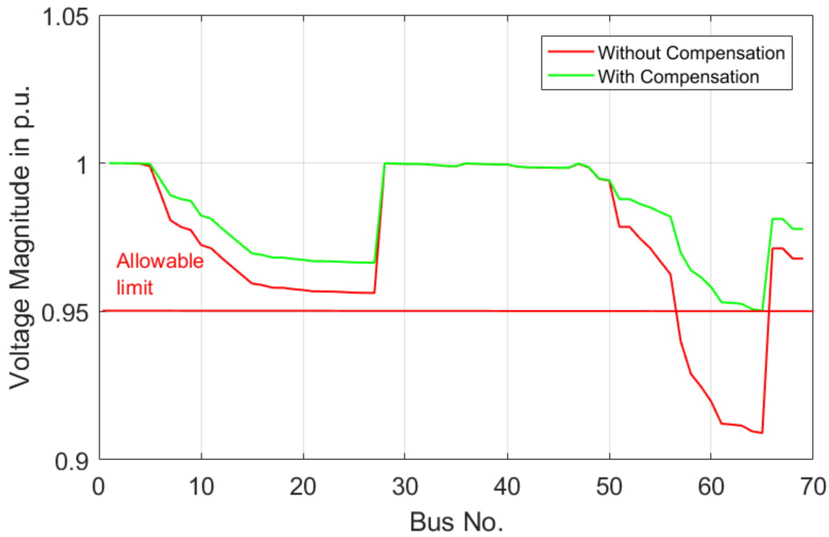

Fig. 5. Comparison of voltage profiles with and without compensation.

Fig. 5 presents the comparison of voltage profiles with and without compensation.

The following improvements are observed:

- Significant voltage rise at buses 55–65 (critical region).
- Reduction in maximum voltage deviation.
- Enhanced voltage stability across the feeder.
- Improved overall voltage regulation.

The improvement is particularly noticeable at the weakest buses, where compensation prevents voltage from falling below the acceptable limit. This confirms that the proposed capacitor placement strategy effectively mitigates voltage drop in the radial distribution network.

D. Discussion

The results confirm that voltage instability in radial distribution systems is primarily caused by reactive power deficiency and feeder impedance. Proper placement of shunt capacitors provides local reactive power support, reduces feeder current, improves voltage profile, and decreases system losses.

The forward–backward sweep method proved to be computationally efficient and stable for analysing the IEEE 69-bus system. The proposed compensation strategy successfully enhances voltage regulation without requiring structural changes to the network.

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V. CONCLUSION

In this paper, load flow analysis of the IEEE 69-bus radial distribution system has been carried out using the forward–backward sweep method. Due to the high resistance-to-reactance ratio and cumulative load demand in radial feeders, significant voltage drop was observed at downstream buses under base case conditions. Several buses operated close to or below the permissible voltage limit, indicating the need for reactive power support.

To mitigate voltage deviation, switched shunt capacitors were installed at selected buses exhibiting maximum voltage drop. The reactive power injected locally reduced feeder current, minimized voltage drop, and improved the overall voltage profile of the system. Simulation results demonstrated that all bus voltages were restored within the acceptable range of ±5% of nominal value after compensation.

Furthermore, the reduction in branch current led to a significant decrease in real power losses, thereby enhancing overall system efficiency. The forward–backward sweep method proved to be computationally efficient and suitable for analyzing radial distribution networks.

The study confirms that proper placement of shunt capacitors is an effective and economical solution for voltage regulation and loss reduction in radial distribution systems. Future work may focus on optimal capacitor sizing using advanced optimization techniques and integration of distributed generation for further performance improvement.

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