

Performance Assessment and Voltage Improvement of a Radial Distribution Network Using ETAP

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ABSTRACT

This study evaluates the steady-state performance of a 6-bus radial distribution network and examines voltage improvement using ETAP load-flow analysis. A base case without compensation is assessed to quantify voltage deviation, feeder and transformer loading, and active/reactive power losses, key planning indicators in distribution networks where voltage drop accumulates along a single supply path. The system, modelled with a 33 kV source stepped down to an 11 kV feeder supplying downstream aggregated loads, is solved using the Newton-Raphson method for its robustness in nonlinear power-flow equations. Results show severe under-voltage at Bus 5 (58.1 %), high branch currents, and substantial technical losses. To enhance performance, shunt capacitor banks are installed at Buses 5 and 6, ranging from 0.5 to 3.0 Mvar in 0.5 Mvar increments to study sensitivity and practical sizing. Post-compensation, bus voltages are restored near nominal (0.999–1.019 pu), branch currents decrease significantly (e.g., 351.6 A to 262.7 A in a critical section), and losses reduce from 1.393 MW to 0.817 MW (41.35%) and 2.429 Mvar to 1.424 Mvar (41.38%). The results confirm that properly placed and sized shunt capacitors effectively improve voltage regulation, reduce loading stress, and minimize losses in radial distribution feeders.

KEYWORDS

ETAP load-flow analysis, radial distribution network, Shunt capacitor bank, Voltage improvement, Technical losses, Branch currents

I. INTRODUCTION

Keeping voltage within safe limits and avoiding overloading are key to reliable power delivery, since both under voltage and excessive loading can damage equipment and shorten its lifespan. Radial distribution networks, which supply power along a single path from the substation, are especially vulnerable to voltage drops and losses. As electricity travels farther along the feeder, voltage decreases and current increases, particularly when reactive power demand is high or power factor is low.

One widely used solution is shunt capacitor compensation, which supplies reactive power locally, improves voltage levels, and reduces system losses. However, many existing approaches look at voltage improvement or loss reduction separately rather than

considering their combined effect on overall system performance. This study takes a more practical approach by using ETAP simulations to assess voltage profile, feeder loading, and power losses together, before and after capacitor installation, providing a more complete view of distribution network performance under real operating conditions.

II. NETWORK MODELLING AND METHODOLOGY

A. ETAP Network Model Description

The study system comprises a six-bus radial distribution network modelled in ETAP to represent a typical medium-voltage feeder supplying downstream loads from a primary substation. The sending end consists of a 33 kV source connected via a step-down transformer to an 11 kV distribution network. Lumped loads are distributed across Buses 3 to 6, consistent with standard load aggregation practices in distribution studies.

The transformer is modelled using its rated capacity and impedance parameters to capture voltage drop and loading effects under varying reactive power demand. This representation is critical, as transformer loading and voltage regulation significantly affect downstream voltage stability and thermal limits (Gönen, 2014). Line segments are modelled using their impedance parameters to account for resistive and reactive voltage drops along the feeder.

The network adopts a strictly radial configuration, with each bus supplied through a single upstream path, reflecting typical distribution system operation and protection requirements (Short, 2014). ETAP is used to compute steady-state bus voltages, branch currents, power flows, transformer loading, and system losses. Two operating conditions are considered: the base case without reactive power compensation and a compensated case with shunt capacitor banks installed at Buses 5 and 6. The capacitor ratings are varied from 0.5 Mvar to 3.0 Mvar in increments of 0.5 Mvar to evaluate system response to incremental compensation. This approach aligns with established capacitor planning practices.

B. Load Flow Solution Method

Power flow analysis is performed using the Newton–Raphson method implemented in ETAP. This method is widely adopted due to its quadratic convergence and numerical robustness in solving the nonlinear power balance equations at system buses. In this formulation, active and reactive power injections are expressed as nonlinear functions of bus voltage magnitudes and phase angles. The Newton–Raphson method iteratively linearizes these equations via the Jacobian matrix and updates voltage estimates until convergence is achieved (Grainger and Stevenson, 1994). Compared with the Gauss–Seidel method, it offers superior convergence speed and accuracy, particularly for multi-bus systems with higher resistance-to-reactance ratios typical of distribution networks.

The method provides reliable computation of bus voltages, power flows, transformer loading, and system losses, forming the basis for evaluating system performance under uncompensated and compensated conditions.

C. Performance Indices

To evaluate system performance comprehensively, three principal indices were adopted: voltage deviation, transformer loading percentage, and total power losses. These indices are widely used in distribution system planning and performance assessment.

1. Voltage Deviation

Voltage deviation shows how far a bus voltage is from the normal value of 1.0 per unit:

$$VD_i = |V_i - 1.0|$$

Voltage should be kept within 0.95 to 1.05 pu for safe and reliable operation (Kersting, 2012). Large deviations usually indicate poor reactive power support and voltage drop along feeders. In radial systems, buses farther from the source tend to have higher deviation due to accumulated impedance.

2. Transformer Loading Percentage

Transformer loading percentage indicates how much of the transformer's capacity is being used:

$$\text{Loading \%} = \frac{S_{\text{actual}}}{S_{\text{rated}}} \times 100$$

Operating near or above rated capacity increases thermal stress and speeds up insulation aging. Sustained overloading reduces transformer lifespan (Kundur, 1994). Monitoring loading ensures that voltage improvement measures do not create excessive upstream stress.

3. Power Losses

Power losses include active and reactive components. Active losses are mainly resistive and follow: $P = I^2R$. Reactive losses are associated with reactive current and system reactance (Grainger & Stevenson, 1994). Reducing losses is important because they represent wasted energy and higher operating costs. Reactive power compensation lowers current, thereby reducing both active and reactive losses (Baran & Wu, 1989).

Evaluating voltage deviation, transformer loading, and power losses together provides a more practical and complete assessment of distribution system performance, aligning with real-world utility planning requirements.

III. BASE OPERATING CONDITIONS AND VOLTAGE IMPROVEMENT IN RADIAL DISTRIBUTION SYSTEMS

Radial distribution networks are simple but prone to voltage drops, high losses, and loading issues, especially at buses far from the substation (weak buses). These buses often fall below acceptable voltage limits (0.95–1.05 p.u.), affecting equipment performance and efficiency. Upstream feeder sections carry cumulative current, leading to increased power losses, while transformers may experience higher loading due to unmet reactive power demand.

To mitigate these issues, reactive power compensation using shunt capacitors is applied. Proper capacitor placement supplies local reactive power, improves voltage profiles (especially at weak buses), reduces system losses, and enhances power factor. The effectiveness of these improvements is evaluated by comparing base and compensated conditions using metrics such as minimum bus voltage, voltage violations, total system

losses, and substation reactive power demand. Successful implementation eliminates under voltage problems and improves overall system performance without causing overvoltage.

IV. RESULTS AND DISCUSSION

A. Results

The simulation outputs and corresponding tabulated results obtained from the study are presented in this section. Figures 1 and 2 illustrate the ETAP models of the six-bus network under the base case and compensated conditions, respectively, while Figure 3 presents the comparative voltage profile for both scenarios.

Tables 1 and 3 summarize the load flow results, including bus voltage magnitudes and other relevant system parameters for the base case and the compensated network. Additionally,

Tables 2 and 4 present key system performance metrics, namely load (MW), load (Mvar), generation (MW), generation (Mvar), active power losses (MW), and reactive power losses (Mvar) for the base case and compensated case, respectively.

These results form the basis for the detailed analysis and discussion presented in the subsequent section.

B. Discussion

1. Base-Case Performance (Without Shunt Capacitor)

Voltage Profile:

The uncompensated 6-bus radial distribution network exhibits a pronounced voltage drop along the feeder

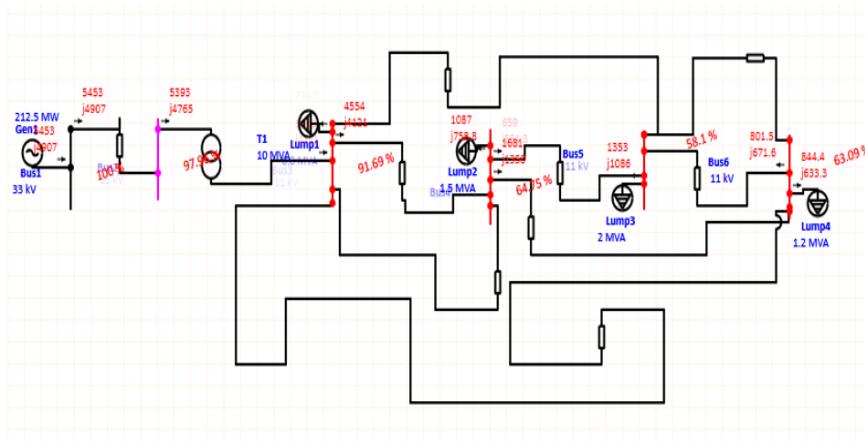


Figure: 1: ETAP Mode of 6 Bus Network Without Shunt Capacitor

While Bus 1 maintains the nominal voltage of 1.00 pu (100%), the downstream buses experience significant under voltage conditions. The recorded voltage magnitudes are as follows: Bus 3 = 0.917 pu, Bus 4 = 0.648 pu, Bus 5 = 0.581 pu, and Bus 6 = 0.630 pu.

The lowest voltage is observed at Bus 5 (58.10%), indicating severe voltage regulation issues and a deficiency in reactive power support within the network.

Table: 1: Load Flow Result without Shunt Capacitor

LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow				XFMR	
ID	kV	% Mag	Ang	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
*Bus1	33.000	100.000	0.0	5.453	4.907	0.000	0.000	Bus2	5.453	4.907	128.3	74.3	
Bus2	33.000	97.960	-0.6	0.000	0.000	0.000	0.000	Bus1	-5.393	-4.765	128.5	74.9	
								Bus3	5.393	4.765	128.5	74.9	
Bus3	11.000	91.690	-4.4	0.000	0.000	0.775	0.000	Bus4	4.554	4.121	351.6	74.2	
								Bus2	-5.329	-4.121	385.6	79.1	
Bus4	11.000	64.751	-8.7	0.000	0.000	1.087	0.759	Bus5	0.659	0.551	69.6	76.7	
								Bus6	1.681	1.350	174.7	78.0	
								Bus3	-3.427	-2.660	351.6	79.0	
Bus5	11.000	58.102	-10.1	0.000	0.000	1.353	1.086	Bus4	-0.604	-0.481	69.7	78.2	
								Bus6	-0.750	-0.605	87.0	77.8	
Bus6	11.000	63.088	-9.1	0.000	0.000	0.844	0.633	Bus5	0.801	0.672	87.0	76.6	
								Bus4	-1.646	-1.305	174.7	78.4	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)
 # Indicates a bus with a load mismatch of more than 0.1 MVA

2. Loading Condition

As presented in Table 1, the base-case scenario exhibits elevated feeder current levels, particularly along the upstream sections supplying downstream loads. Currents of approximately 351.6 A and 385.6 an are recorded in critical feeder branches. This indicates substantial reactive power flow from the source, resulting in increased apparent power transfer and higher conductor loading.

3. System Losses

Table 2 shows that the system experiences active power losses of 1.393 MW and reactive power losses of 2.429 Mvar. Considering a total load demand of 4.059 MW and 2.478 Mvar, these losses are relatively high, thereby confirming inefficient system operation in the uncompensated state.

Table 2: system performance metrics (Base Case Result)

Load-MW	4.059
Load-Mvar	2.478
Generation-MW	5.453
Generation-Mvar	4.907
Loss-MW	1.393
Loss-Mvar	2.429

4. Performance after Shunt Capacitor Installation (Bus 5 and Bus 6)

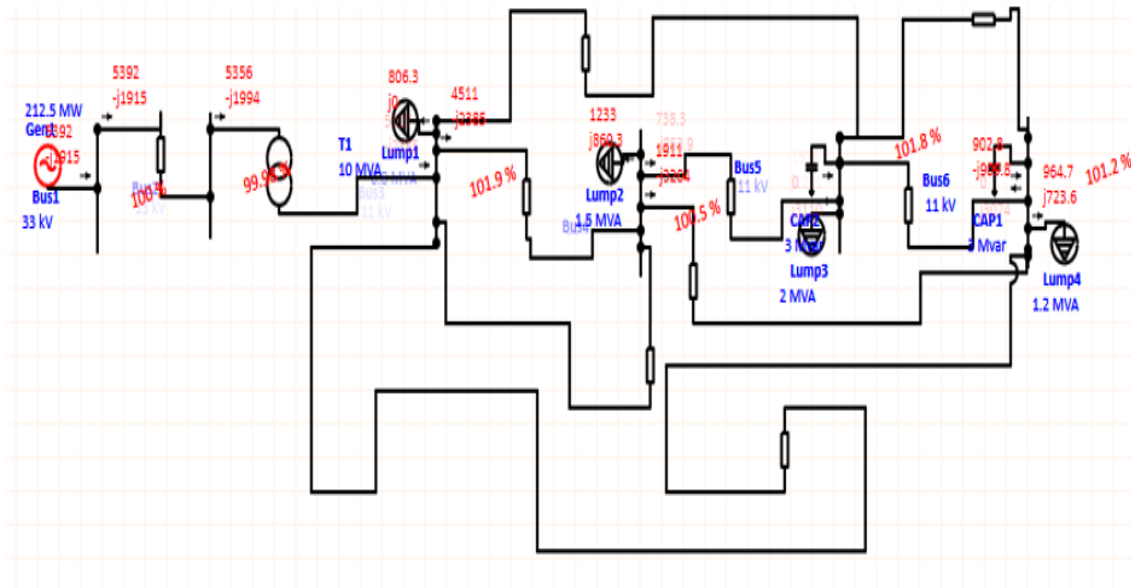


Figure: 2: ETAP Mode of 6 Bus Network Shunt Capacitor Connected at Bus 5 & 6

Shunt capacitors were installed at Bus 5 and Bus 6. The capacitor size was varied from 0.5 Mvar in steps of 0.5 Mvar up to 3.0 Mvar.

The final configuration produced the improved load flow results discussed below.

LOAD FLOW REPORT

Bus		Voltage		Generation		Load		Load Flow				XFMR	
ID	kV	% Mag	Ang	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap
*Bus1	33.000	100.000	0.0	5.392	-1.915	0.000	0.000	Bus2	5.392	-1.915	100.1	-94.2	
Bus2	33.000	99.982	-1.0	0.000	0.000	0.000	0.000	Bus1	-5.356	1.994	100.0	-93.7	
								Bus3	5.356	-1.994	100.0	-93.7	
Bus3	11.000	101.941	-4.8	0.000	0.000	0.806	0.000	Bus4	4.511	-2.385	262.7	-88.4	
								Bus2	-5.317	2.385	300.0	-91.2	
Bus4	11.000	100.510	-16.4	0.000	0.000	1.233	0.860	Bus5	0.738	-0.854	58.9	-65.4	
								Bus6	1.911	-3.204	194.8	-51.2	
								Bus3	-3.882	3.198	262.6	-77.2	
Bus5	11.000	101.813	-19.6	0.000	0.000	1.571	-1.849	Bus4	-0.699	0.902	58.8	-61.2	
								Bus6	-0.873	0.947	66.4	-67.8	
Bus6	11.000	101.227	-17.4	0.000	0.000	0.965	-2.350	Bus5	0.903	-0.910	66.5	-70.4	
								Bus4	-1.868	3.260	194.8	-49.7	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)
 # Indicates a bus with a load mismatch of more than 0.1 MVA

Table: 3: Load Flow Result with Shunt Capacitor Added at Bus 5 & 6

The improvement can be attributed to the localized injection of reactive power by the installed capacitors, which effectively reduced voltage drops along feeder reactance and enhanced overall voltage regulation within the system.

5. *Loading Improvement*

As illustrated in table 3, a significant reduction in branch currents was achieved following the installation of shunt capacitors. For instance, the current in a critical feeder section decreased from approximately 351.6 A to 262.7 A. This reduction in current enhances the thermal operating margins of the conductors and increases the effective capacity of the feeder.

6. *Loss Reduction*

A substantial reduction in system losses was also observed, as shown in table 4. The active power loss decreased from 1.393 MW to 0.817 MW, representing a 41.35% reduction, while the reactive power loss declined from 2.429 Mvar to 1.424 Mvar, corresponding to a 41.38% reduction. This improvement is primarily attributed to the reduction in current magnitude, which directly lowers the I²R losses along the feeder.

Table 4: system performance metrics (Compensation Result)

Load-MW	4.575
Load-Mvar	-3.339
Generation-MW	5.392

Generation-Mvar	-1.915
Loss-MW	0.817
Loss-Mvar	1.424

7. Voltage Profile Improvement

The voltage profile of the system before and after compensation is illustrated in Figure 3. Under base-case conditions, voltage decreases progressively along the feeder due to cumulative impedance effects, reaching a minimum value of 0.581 pu at Bus 5, which is well below the acceptable limit of 0.95 pu. This indicates poor voltage regulation and inadequate reactive power support, particularly at downstream buses. Following the installation of shunt capacitors at Bus 5 and Bus 6, a significant improvement in voltage profile was achieved across the network. All bus voltages were restored within acceptable operating limits, ranging approximately from 0.999 pu to 1.019 pu. Specifically, the post-compensation voltages were recorded as: Bus 2 = 0.9998 pu, Bus 3 = 1.0194 pu, Bus 4 = 1.0051 pu, Bus 5 = 1.0181 pu, and Bus 6 = 1.0123 pu.

Substantial voltage recovery was observed at previously under-voltage buses, with Bus 4 improving from 0.6475 pu to 1.0051 pu, Bus 5 from 0.5810 pu to 1.0181 pu, and Bus 6 from 0.6304 pu to 1.0123 pu. These results confirm the effectiveness of reactive power compensation in mitigating voltage drop and enhancing overall system performance.

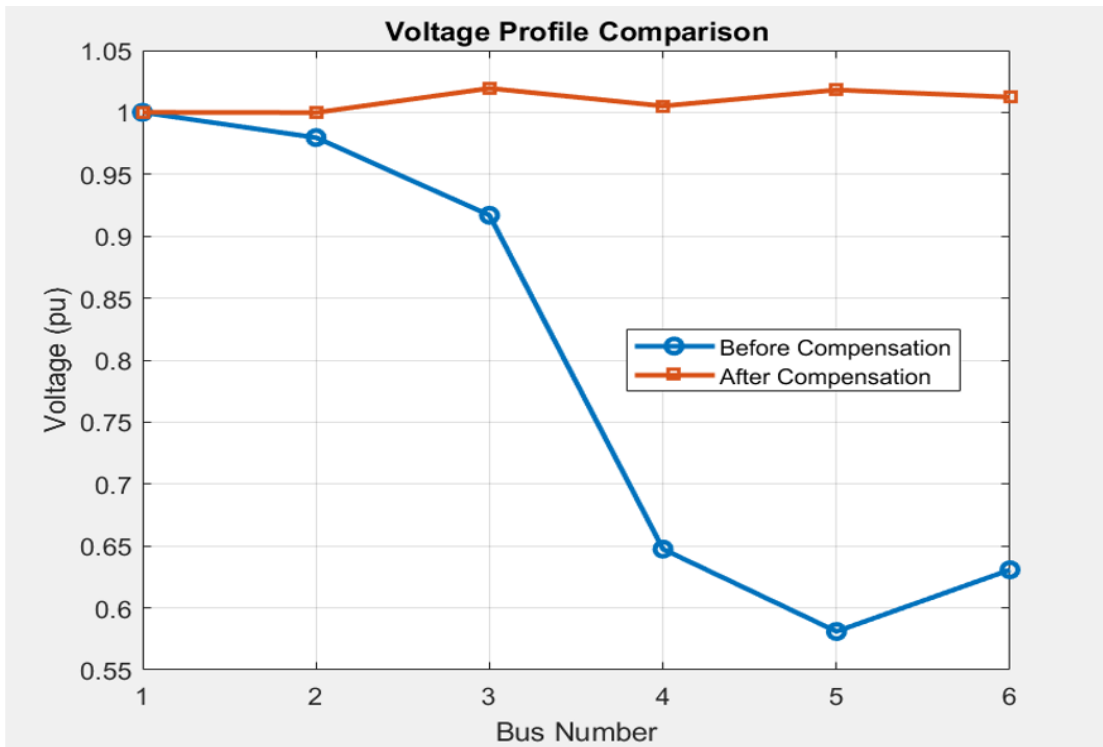


Figure: 3: Voltage Profile of 6 Bus System Before & After Compensation

C. *Power Factor Analysis*

Power factor is a critical performance indicator in distribution systems, as it directly influences current magnitude, system losses, and voltage regulation. Low power factor conditions result in higher current flow for the same active power demand, leading to increased losses and poor voltage profiles.

1. *Base Case (Without Shunt Capacitor)*

Table 1 shows that the power factor along the feeder ranges approximately from 0.74 to 0.79 (lagging), indicating a substantial reactive power demand within the system. For example, at a critical section of the feeder, a power factor of about 0.742 is recorded at a current of 351.6 A, while upstream sections exhibit power factor values within the range of 0.74 to 0.79. These relatively low power factor values suggest that a significant portion of the line current is reactive. Consequently, this leads to increased current magnitude, higher (I^2R) losses, and pronounced voltage drops, particularly toward the downstream buses. This condition accounts for the observed under voltage issues in the system, with the most severe case occurring at Bus 5, where the voltage drops to approximately 0.581 pu.

2. *Compensated Case (With Shunt Capacitor at Bus 5 and 6)*

Following the installation of shunt capacitors at Buses 5 and 6, the system exhibits a significant improvement in power factor characteristics, as shown in Table 3. The power factor values increase substantially and, in some branches, transition from lagging to leading. For example, the power factor improves from approximately 0.74 lagging to about 0.88 leading, while the corresponding current decreases from 351.6 A to 262.7 A. The introduction of shunt capacitors provides local reactive power support, thereby reducing the amount of reactive power drawn from the source. As a result, the system experiences an overall improvement in power factor, bringing it closer to unity or slightly into the leading range. Additionally, the line current magnitude is reduced, which in turn minimizes feeder losses and enhances the voltage profile across all buses.

3. *Engineering Interpretation*

The improvement in power factor demonstrates the effectiveness of reactive power compensation in minimizing unnecessary current flow. While slight leading power factor is acceptable, excessive leading conditions should be avoided as they may result in overvoltage or instability under light load conditions. The results confirm that power factor correction is a key mechanism through which shunt capacitors enhance distribution system performance, complementing voltage improvement and loss reduction.

D. *Capacitor Sizing Trend (0.5–3.0 Mvar):*

As the capacitor size increased from 0.5 to 3.0 Mvar, the system showed progressive improvement in performance, with better voltage profiles, a gradual reduction in feeder

current, and a significant decrease in system losses. However, the rate of improvement became less pronounced at higher compensation levels, indicating diminishing returns. The compensated-case results presented in Tables 3 and 4 and Figure 3 correspond to 3.0 Mvar shunt capacitor banks installed at both Bus 5 and Bus 6.”, which was selected as the final compensation level. At this level, all bus voltages remained within the acceptable range of 0.999–1.019 pu without causing excessive overvoltage conditions.

E. Overall Performance Assessment

Prior to compensation, the system exhibited severe under voltage conditions at downstream buses, accompanied by high feeder loading and significant system losses. Following the implementation of reactive power compensation, the voltage profile was restored to values close to 1.0 per unit across the network. In addition, the loading condition of the feeder improved considerably, and a substantial reduction of approximately 41% in both active and reactive power losses was achieved, indicating a marked enhancement in overall system performance.

V. CONCLUSION AND RECOMMENDATIONS

A. Conclusion

This study evaluated the performance of a 6-bus radial distribution network using ETAP, focusing on voltage profile, feeder loading, and system losses before and after reactive power compensation. The base-case analysis revealed significant technical weaknesses typical of heavily loaded radial systems. Severe voltage drops were observed at the downstream buses, with Bus 5 and Bus 6 operating far below acceptable limits. High branch currents were recorded along the main feeder sections, resulting in considerable active and reactive power losses. The installation of shunt capacitors at Bus 5 and Bus 6 produced substantial technical improvements. Voltage magnitudes across all buses were restored to values close to 1.0 pu, eliminating the under-voltage condition. Feeder current levels decreased noticeably, reducing thermal stress on conductors and improving the overall loading margin. Most importantly, system losses were reduced by approximately 41% for both active and reactive components. The stepwise variation of capacitor size from 0.5 Mvar to 3.0 Mvar demonstrated a consistent improvement trend: voltage increased progressively, current magnitude decreased, and losses reduced significantly. The final selected compensation level achieved a well-balanced performance without introducing unacceptable overvoltage conditions. On the whole, the results confirm that properly placed and adequately sized shunt capacitors are highly effective for improving voltage regulation, reducing feeder loading, and enhancing energy efficiency in radial distribution systems.

B. Recommendations

1. Strategic Placement of Capacitors

Utilities should prioritize installing shunt capacitors at electrically weak and remote buses where voltage drops are most severe. Locating capacitors near high reactive demand points maximizes voltage support and minimizes reactive power flow from the substation.

2. *Optimal Sizing Based on Load Flow Studies*

Capacitor sizing should be determined through detailed load flow simulations rather than rule-of-thumb estimates. Incremental analysis, as demonstrated in this study, helps identify the point where loss reduction and voltage improvement are maximized without causing overcompensation.

3. *Voltage Regulation Standards Compliance*

Distribution utilities must ensure that bus voltages remain within statutory limits (typically 0.95–1.05 pu). Reactive compensation planning should aim to maintain voltage stability under both peak and light-load conditions.

4. *Loss Reduction as an Economic Strategy*

The significant reduction in active power losses highlights the economic benefits of reactive power compensation. Utilities should incorporate loss minimization objectives into their distribution planning strategies to improve operational efficiency and reduce generation costs.

5. *Provision for Future Load Growth*

Improved voltage profile and reduced feeder loading increase system capacity margins. Utilities can use capacitor installation not only for present correction but also as a cost-effective alternative to immediate feeder reinforcement.

6. *Adoption of Automatic or Switched Capacitor Banks*

To prevent leading power factor issues during low-load periods, utilities are encouraged to implement switched or automatically controlled capacitor banks. This ensures adaptive reactive power support based on real-time demand.

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