



Original Research

Distribution feeder reconfiguration and optimal capacitor placement for power loss and voltage profile improvement: a case study of Nekemte distribution system, Ethiopia

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Abstract

Distribution systems in developing countries often experience high technical losses and poor voltage profiles due to radial configurations and inadequate reactive power compensation. This study investigates feeder reconfiguration and optimal capacitor placement to minimize losses and improve voltage profiles in the Nekemte distribution system, Ethiopia. We modeled a 45-bus Hospital Feeder with a 5.63 MW peak load in DIgSILENT PowerFactory and evaluated three scenarios: feeder reconfiguration, optimal capacitor placement, and their combined application. The Loss Sensitivity Factor identified candidate buses, while the economic analysis considered energy losses and capacitor investment costs. Feeder reconfiguration reduced active power loss from 0.36 to 0.25 MW (30.5%) and increased average and minimum bus voltages from 0.9347 to 0.9546 pu and 0.900 to 0.936 pu, respectively. Capacitor placement reduced loss to 0.27 MW (25.0%) and increased these voltages to 0.9512 and 0.925 pu. The combined approach achieved the best performance, reducing loss to 0.20 MW (44.4%) and increasing average and minimum voltages to 0.9652 and 0.943 pu, respectively. It achieved annual savings of \$52,080 and a payback period of 0.345 years. The contribution is an integrated technical-economic assessment of coordinated reconfiguration and capacitor placement for a practical Ethiopian distribution feeder.

Article Information

Article History:

Received: 30-05-2026

Revised: 23-08-2026

Accepted: 28-09-2026

Keywords:

*Distribution system;
Feeder reconfiguration;
Optimal capacitor
placement; Power loss
minimization; Dig
Silent Power Factory*

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INTRODUCTION

The distribution system represents the final stage of electric power delivery, connecting transmission substations to end consumers. In developing countries such as Ethiopia, distribution networks predominantly operate as radial systems because they require lower initial investment and simpler operations (Saadat, 1999). However, this configuration inherently suffers from higher

technical losses and voltage-drop issues than meshed or loop systems (Saadat, 1999).

Technical power losses in distribution systems arise from multiple factors, including conductor resistance (I^2R losses), transformer losses, and low-power-factor operation (Haider et al., 2021). These losses typically account for 70–80% of total system losses, representing significant economic burdens for utility companies and contributing to

inefficient resource utilization (Tahir et al, 2022). Furthermore, voltage profile degradation affects power quality, potentially causing equipment malfunction, reduced motor efficiency, and customer dissatisfaction (Sallam et al., 2011).

The Nekemte distribution system in western Ethiopia exemplifies these challenges. Serving a population of approximately 110,757 with electricity supplied through a 132/15 kV substation, the system experiences substantial technical losses and voltage violations. The Hospital Feeder (K04), a critical 45-bus radial feeder supplying 72 distribution transformers with a peak load of 5.63 MW, exhibits a minimum voltage of 0.900 pu—below the acceptable limit of 0.95 pu—and active power losses of 0.36 MW.

Two primary strategies exist for addressing these issues: (1) *network reconfiguration*, which modifies the topological structure by changing switch statuses to optimize power flow (Narimani et al, 2013); and (2) *optimal capacitor placement*, which installs shunt capacitors to provide reactive power compensation and reduce current flow (Muthukumar & Jayalalitha, 2015). While numerous studies have examined these methods independently, limited research has evaluated their combined application in real-world distribution systems of developing countries.

Significant research has focused on distribution system optimization, broadly categorized into network reconfiguration, capacitor placement, and distributed generation integration. Jayabarathi et al. (2024) proposed deterministic and heuristic techniques that combine the minimum spanning tree algorithm with genetic algorithms (GAs) for network reconfiguration and capacitor placement on 33-bus and 69-bus test systems. Their approach achieved notable loss reductions but relied on simplified topological algorithms that may not capture complex operational constraints.

Vulasala et al. (2009) applied GA to feeder reconfiguration in unbalanced three-phase distribution systems, demonstrating fewer switching operations than conventional methods. Gonzalez et al. (Dzafic et al., 2014) developed a

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sensitivity-analysis-based approach to rapidly compute optimal switching configurations, trading marginal accuracy for substantial computational efficiency.

(Purlu & Turkay, 2022) introduced a heuristic method using branch current as switching indices, requiring only a single power flow calculation. While computationally efficient, their approach may converge to local optima in complex networks. Diaaeldin et al. (2019) proposed the Selective Particle Swarm Optimization (SPSO) technique, combined with a Power-Voltage Sensitivity Constant (PVSC), for simultaneous network reconfiguration and DG/capacitor allocation. Alharbi et al. (2026) combined the Salp Swarm Algorithm (SSA) with Loss Sensitivity Factor (LSF)-based fuzzy logic control for optimal capacitor sizing and placement. Muhammad et al, (2020) examined feeder reconfiguration with DG placement, focusing on photovoltaic and wind generation types. While DG integration offers benefits, their study did not address voltage fluctuation problems and protection coordination challenges associated with DG penetration.

Statement of the problem

Electric power distribution systems are expected to deliver electrical energy efficiently, reliably, and with acceptable voltage quality. However, technical power losses remain a major challenge affecting distribution network performance. These losses primarily result from the inherent resistance of conductors, transformers, transmission and sub-transmission lines, and other distribution system components (Junxia et al., 2014). Energy dissipation in these components not only reduces the distribution network's overall efficiency but also adversely affects reliability, voltage stability, and the quality of power supplied to consumers.

As technical losses increase along distribution feeders, significant voltage drops occur from the sending end to the receiving end of the network (Zhao et al, 2020). Consequently, distribution transformers receive lower-than-rated primary voltage, resulting in inadequate secondary voltage supplied to customers. This condition negatively

affects both utility operations and customer equipment, leading to several operational problems such as transformer overloading, excessive voltage drops at the primary and secondary sides of distribution transformers, poor voltage regulation at customer terminals, increased current drawn by induction motors due to undervoltage, and overloading of distribution feeders as demand continues to grow.

These technical challenges not only degrade distribution system performance but also increase operating costs, reduce equipment lifespan, and diminish customer satisfaction. Therefore, effective techniques are required to reduce technical power losses while maintaining acceptable voltage profiles and enhancing system reliability.

Among the available approaches, distribution feeder reconfiguration and optimal capacitor placement have emerged as effective strategies for improving the operational performance of distribution networks. Feeder reconfiguration minimizes losses by changing the network topology while maintaining a radial structure. In contrast, capacitor placement provides reactive power compensation, reducing current flow and improving voltage profiles (Oshiro et al., 2010). However, the combined effectiveness of these techniques under different loading conditions requires further investigation to achieve optimal technical and economic benefits.

Therefore, this study proposes integrating distribution feeder reconfiguration and optimal capacitor placement to minimize technical power losses, improve voltage profiles, enhance system reliability, and increase customer satisfaction while considering the economic aspects of power loss reduction. The effectiveness of the proposed approach will be evaluated through simulation using DlgSILENT PowerFactory.

Research questions

1. How does the integrated application of distribution feeder reconfiguration and optimal capacitor placement affect technical power losses in the distribution network?
2. To what extent does the proposed approach improve the voltage profile and operational performance of distribution feeders under different loading conditions?
3. What are the technical and economic benefits of applying distribution feeder reconfiguration and optimal capacitor placement compared with the existing distribution network configuration?

MATERIALS AND METHODS

Study system description

The Nekemte distribution substation receives 132 kV power from the Fincha'a hydroelectric plant via the Bako and Didesa substations. The substation contains two power transformers (25 MVA, 132/15 kV, and 20/16 MVA, 132/33 kV) that supply seven outgoing feeders, as shown in [Figure 1](#). This study focuses on the Hospital Feeder (K04), a radial 15 kV distribution feeder selected as the case study due to its operational importance and load characteristics. The feeder has 45 buses and is supplied by 72 distribution transformers with capacities ranging from 25 kVA to 400 kVA. During peak demand, the feeder carries an active power load of 5.63 MW and a reactive power load of 3.88 MVAR, operating at an average power factor of 0.85. The feeder extends about 28 km from the distribution substation and serves a diverse range of residential, commercial, and critical customers, including healthcare facilities. These characteristics make the Hospital Feeder (K04) an appropriate representative network for evaluating distribution system performance and assessing the effectiveness of the proposed optimization techniques.

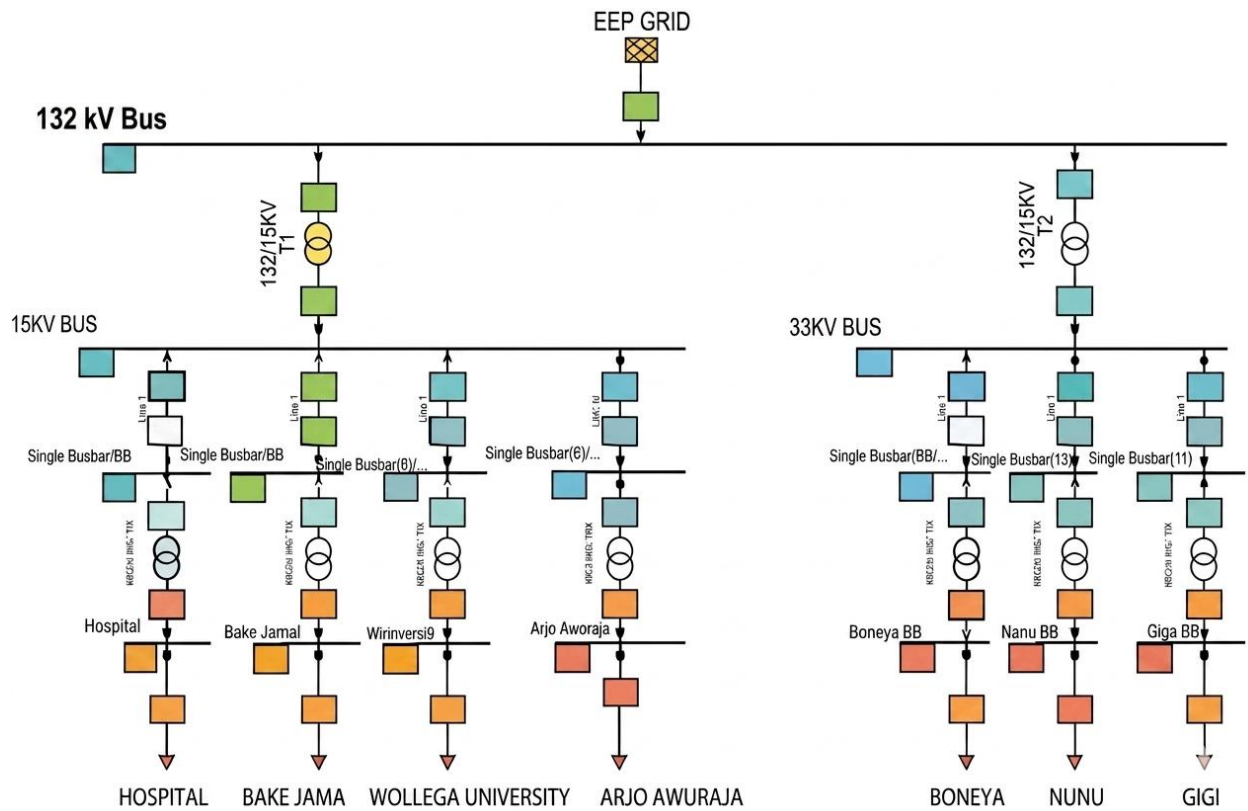


Figure 1. Single Line Diagram of Nekemte Distribution System

Optimization approaches

Three optimization scenarios were investigated:

Case I: Feeder reconfiguration only.

The network topology was modified by changing the status of tie switches (normally open) and sectionalizing switches (normally closed) to transfer loads between feeders while maintaining radial topology. The objective function minimizes total active power loss:

$$\min F = \sum_{i=1}^n \frac{P_i^2 + Q_i^2}{|V_i|^2} r_i \cdot S_i \quad (1)$$

where P_i and Q_i are the active and reactive power flows in branch i , V_i is the node voltage, r_i is the branch resistance, S_i is the switch status (0=open, 1=closed), and n is the number of branches.

Case II: Optimal capacitor placement only

Shunt capacitors were installed at strategically selected buses to provide reactive power compensation. We considered fixed and switched

capacitor banks, with sizes ranging from 0.5 MVAR to 1.0 MVAR.

Case III: Combined approach.

We applied both feeder reconfiguration and optimal capacitor placement simultaneously to achieve synergistic benefits.

Loss sensitivity factor for candidate bus selection

The Loss Sensitivity Factor (LSF) method was employed to identify candidate buses for capacitor placement. The LSF represents the rate of change of power loss with respect to reactive power injection:

$$\text{LSFi} = \frac{\partial P_L}{\partial Q_i} = \frac{2Q_i \cdot R_i}{|V_i|^2} \quad (2)$$

where Q_i is the reactive power at bus i , R_i is the resistance from the source to bus i , and V_i is the voltage at bus i .

LSF ranked buses in descending order. A normalized voltage magnitude criterion was applied:

$$\text{Norm}[i] = \frac{V_i}{V_{base}} \quad (3)$$

Buses with $\text{Norm}[i] < 1.05$ were selected as candidate locations for capacitor installation.

Objective function and constraints

The comprehensive objective function minimizes total annual cost:

$$\min C_{total} = C_{loss} + C_{cap} \quad (4)$$

Where, C_{loss} is the annual cost of energy losses and C_{cap} is the annualized capacitor cost.

Power loss cost

$$C_{loss} = C_{energy} \cdot P_{loss} \cdot T \quad (5)$$

where C_{energy} is the cost per kWh (\$0.05/kWh), P_{loss} is the power loss in kW, and T is the annual operating hours (8,760 hours).

Capacitor cost

Capacitor cost includes the cost of installation plus the cost to purchase the capacitor and operation and Maintenance cost.

$$C_{cap} = C_{install} + (C_{CV} \cdot Q_{ck}) + C_{O\&M} \quad (6)$$

Where:

C_{cap} is capacitor cost per year, $C_{install}$ is the capacitor installation cost, C_{CV} is the capacitor cost per kVAR, Q_{ck} is the capacitor rating in bus K in KVAR, $C_{O\&M}$ is the operation and maintenance cost

Operational constraints

The distribution system operation was subject to several technical constraints to ensure safe, reliable, and efficient network performance. Bus voltage magnitudes were maintained within the permissible operating limits of $0.95 \text{ p.u.} \leq |V_i| \leq 1.05 \text{ p.u.}$ to ensure acceptable voltage quality for all connected customers. Branch current loading

Sci. Technol. Arts Res. J., July –Sep, 2026, 15(3), 01-10 was constrained such that the current flowing through each branch did not exceed its maximum thermal rating ($|I_i| \leq I_{i, \text{max}}$), thereby preventing conductor overloading and equipment damage. Furthermore, the network was required to maintain a radial topology throughout the optimization process to preserve the operational characteristics and protection coordination of the distribution system. Finally, the system had to satisfy the power flow balance equations, ensuring that the generated and supplied power matched the total load demand and system losses at every bus, thereby maintaining steady-state operating equilibrium.

Simulation environment

All simulations were performed using *DigSilent Power Factory 15.1.6*, commercial power system analysis software widely used for distribution system planning and operation. We used the Newton-Raphson load-flow method with the current-equation formulation for its superior convergence in distribution systems.

RESULTS AND DISCUSSION

Results

Baseline system performance

The existing Hospital Feeder operates with significant technical losses and voltage violations. [Table 1](#) shows that the voltage profile analysis reveals significant undervoltage conditions at the feeder extremities, with a minimum voltage of 0.900 pu at the most remote bus. This 10% voltage deviation exceeds utility standards and may impair customer equipment operation.

Table 1

Baseline System Performance (Existing Configuration)

Parameter	Value
Active Power Loss	0.36 MW
Reactive Power Loss	0.32 MVAR

Table 1 continues.

Minimum Bus Voltage	0.900 pu
Maximum Bus Voltage	1.000 pu
Annual Energy Loss Cost	\$157,680
Buses Below 0.95 pu	5 (buses 34, 35, 41, 44, 45)

Case I: Feeder Reconfiguration Results

Table 2 presents the reconfiguration results. The optimal switching strategy involved modifying tie switch positions from the original configuration {S14, S19, S27, S34, S40} to {S9, S14, S19, S27, S45, S46}. Table 2 shows that network-

- reconfiguration achieved a 30.5% reduction in active power losses by redistributing load currents across alternative paths, thereby reducing the overall I²R losses. The minimum voltage improved significantly to 0.936 pu, although it remained slightly below the target value of 0.95 pu.

Table 2

Feeder Reconfiguration Results (Case I)

Parameter	Original	Reconfigured
Active Power Loss (MW)	0.36	0.25
Reactive Power Loss (MVAR)	0.32	0.23
Minimum Voltage (pu)	0.900	0.936
Maximum Voltage (pu)	1.000	1.000
Loss Reduction (%)	–	30.5%
Annual Savings (USD)	–	\$48,180

Case II: Optimal Capacitor Placement Results

Using the Loss Sensitivity Factor analysis, buses 35, 40, and 41 were identified as optimal capacitor

locations. Table 3 details the capacitor allocation and resulting performance.

Table 3

Optimal Capacitor Placement Results (Case II)

Parameter	Value
Capacitor at Bus 35	1.0 MVAR
Capacitor at Bus 40	0.5 MVAR
Capacitor at Bus 41	0.5 MVAR
Total Capacitor Investment	\$18,000
Active Power Loss (MW)	0.27
Reactive Power Loss (MVAR)	0.19
Minimum Voltage (pu)	0.925
Loss Reduction (%)	25.0%
Annual Savings (USD)	\$21,420

Case III: Combined Approach Results

The combined optimization integrated feeder reconfiguration with capacitor placement at buses

35, 40, and 41. Table 4 presents the comprehensive results. The capacitor placement reduced reactive power flow in the feeder, thereby decreasing

current magnitude and the associated power losses. The minimum voltage improved to 0.925

pu, representing a 2.8% improvement over the baseline case.

Table 4

Combined Optimization Results (Case III)

Parameter	Original	Optimized	Improvement
Active Power Loss (MW)	0.36	0.20	44.4%
Reactive Power Loss (MVAR)	0.32	0.17	46.9%
Minimum Voltage (pu)	0.900	0.942	4.7%
Maximum Voltage (pu)	1.000	1.019	–
Annual Loss Cost (USD)	157,680	105,600	\$52,080
Capacitor Investment (USD) –	–	18,000	–
Net Annual Savings (USD)	–	–	\$52,080
Payback Period (years)	–	0.345	–

Table 4 shows that the combined approach achieved synergistic benefits that exceeded the improvements from either method alone. The 44.4% reduction in active power losses represents the best performance among all the tested scenarios. The combined approach demonstrates

clear superiority: (i) 44% greater loss reduction than reconfiguration alone; (ii) 78% greater loss reduction than capacitors alone; and (iii) the best voltage profile improvement among all scenarios. Table 5 illustrates the comparative performance of all optimization approaches across key metrics.

Table 5

Comparative performance of all optimization approaches across key metrics.

(a) Active Power Loss Comparison		(b) Minimum Voltage Comparison	
Scenario	Loss (MW)	Scenario	Min V (pu)
Original	0.36	Original	0.900
Reconfiguration	0.25	Reconfiguration	0.936
Capacitor Only	0.27	Capacitor Only	0.925
Combined	0.20	Combined	0.943

Discussion

The economic analysis demonstrates that the combined distribution feeder reconfiguration and optimal capacitor placement strategy is highly cost-effective and financially attractive. The total investment required for capacitor installation is estimated at USD 18,000, while the proposed solution yields annual energy savings of approximately 1,401.6 MWh. These energy savings translate into an estimated annual cost saving of USD 52,080, providing substantial economic benefits to the utility. The investment

can be recovered within a simple payback period of only 0.345 years (approximately 4.1 months), indicating rapid capital recovery. Furthermore, the project achieves a net present value (NPV) of USD 302,089 over a 10-year project lifetime at a 10% discount rate, confirming its strong long-term financial viability. The annual return on investment (ROI) of 289% further highlights the exceptional profitability of the proposed approach, demonstrating that the combined strategy not only enhances technical performance through reduced power losses and improved voltage profiles but

also delivers significant economic returns, making it an attractive investment for distribution network modernization. The exceptionally short payback period (4.1 months) makes this investment highly attractive for utility operators with limited capital budgets.

CONCLUSIONS

This study investigated distribution feeder reconfiguration and optimal capacitor placement to minimize power losses and improve the voltage profile of the Nekemte distribution system in Ethiopia. The findings indicate that the existing Hospital Feeder experienced significant technical losses of 0.36 MW and severe voltage violations, with a minimum bus voltage of 0.900 pu, primarily due to its radial configuration and insufficient reactive power compensation. Feeder reconfiguration alone substantially improved performance by reducing active power losses by 30.5% and increasing the minimum voltage to 0.936 pu through optimal load redistribution. Similarly, optimal capacitor placement alone reduced power losses by 25.0% and improved the minimum voltage to 0.925 pu, demonstrating the effectiveness of reactive power compensation in improving radial distribution network performance. However, the combined application of feeder reconfiguration and optimal capacitor placement yielded the best overall performance, achieving a 44.4% reduction in active power losses (from 0.36 MW to 0.20 MW), increasing the minimum voltage from 0.900 pu to 0.943 pu, generating annual cost savings of approximately USD 52,080, and providing a payback period of only 0.345 years (approximately 4.1 months). Furthermore, the Loss Sensitivity Factor (LSF) method proved effective for identifying optimal capacitor locations by reducing the search space and computational complexity. Overall, the economic analysis confirms that the integrated optimization approach is a highly cost-effective solution for improving distribution system performance and reliability, offering a practical and economically attractive alternative to costly

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infrastructure expansion, particularly for electric utilities in developing countries.

Recommendations

Based on this study's findings, several recommendations are proposed to help distribution utilities improve the technical performance, reliability, and economic efficiency of medium-voltage distribution systems. Distribution utilities should prioritize combined optimization strategies that integrate distribution feeder reconfiguration with optimal capacitor placement, rather than relying on single-method approaches, because the combined strategy provides superior technical and economic benefits. Utilities should also deploy automated switching systems to enable dynamic feeder reconfiguration in response to changing load conditions, improving operational flexibility and minimizing power losses. Furthermore, utilities should establish comprehensive data management systems to support accurate load forecasting, continuous performance monitoring, and informed operational decision-making. Similar optimization studies should be extended to other feeders within the Nekemte distribution system as well as to comparable distribution networks across Ethiopia to maximize system-wide benefits. The economic analysis indicates that the proposed optimization strategy is highly cost-effective, yielding an annual return on investment (ROI) of approximately 289%, making it an attractive and sustainable investment for modern distribution network planning and operation.

CRedit Authorship Contribution Statement

Ginbar Ensermu: Conceptualization, methodology, supervision, validation, writing original draft, writing – review & editing, and corresponding author responsibilities. Ginbar Ensermu also prepared and finalized the manuscript.

Roba Mare: Formal analysis, investigation, software, data curation, validation, writing original

Declaration of competing interests

The authors declare that they have no known competing interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

This study did not involve human participants, human biological materials, animals, or personal data requiring ethical approval. The research used electrical distribution network data, engineering analyses, and computer-based simulations. The authors obtained permission to use the technical data from the relevant utility authorities, where required.

Data availability statement

The data supporting this study's findings are available from the authors upon reasonable request. Some of the distribution network data used in this research are subject to institutional and utility confidentiality restrictions and therefore cannot be made publicly available.

Acknowledgments

The authors sincerely acknowledge Wollega University, Institute of Technology, for providing the academic and research environment that supported this study. The authors also thank the Ethiopian Electric Utility (EEU), Nekemte Region Distribution Office, for providing the technical data and valuable information required for this research. The authors appreciate all individuals who provided technical advice and constructive comments during this work.

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