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Optimal Configuration of Biratnagar Radial Distribution System for Loss Minimization and Voltage Improvements

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Abstract

Nepal's electrical distribution systems face challenges, such as excessive technical losses and inadequate voltage regulation, particularly in urban centers like Biratnagar. The 33 kV radial distribution network experiences power losses of 5.155 MW (13.6% of the supplied power) and minimum voltages of 94.2%, which is below the acceptable standard of 95%. This study investigates three reconfiguration strategies using the ETAP software with Nepal Electricity Authority (NEA) 2025 operational data: distributed generation (DG) with rooftop photovoltaic systems at 25% penetration, conductor upgrading to higher-capacity ACSR types, and shunt capacitor bank placement at alternative voltage levels. The distributed generation achieved a 31.2% loss reduction to 3.549 MW while improving the minimum voltage to 95.9%. Conductor upgrading provides a maximum loss reduction of 46.5% to 2.757 MW with a voltage improvement of 96.1%. Capacitor banks at 11 kV enhance the voltage profile to 96.9% with a 32.5% loss reduction, whereas 33 kV placement achieves 28.4% loss reduction with inferior voltage support. Each strategy impacts system performance differently: conductor upgrading reduces conductor resistance, DG systems reduce the transmission current through local generation, and 11 kV capacitors provide reactive power support where voltage drops are critical. The analysis shows that no strategy optimizes all performance metrics, revealing trade-offs between loss reduction and voltage improvement. This research provides the NEA with a technical comparison to select strategies aligned with loss minimization or voltage quality improvement priorities.

Keywords: ACSR conductor • Biratnagar distribution • Distributed generation • ETAP simulation • Power Loss • Voltage profile improvement

1. Introduction

A reliable electrical distribution network is essential for economic growth and the quality of life. In Nepal, radial distribution networks often experience high technical losses and unstable voltage. The Biratnagar system, which supplies power to one of Koshi Province's largest cities, highlights these issues. It receives power from the Duhabi Grid via 33 kV radial feeders and supplies the Rani, Tanki, and Katahari substations.

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As infrastructure ages and demand rises, conductors become overloaded, leading to high losses and unacceptable voltage drops at consumer terminals.Akhtar et al. (2021) The Nepal Electricity Authority (NEA) reports that total system losses are between 15 and 20 percent, with much of this due to distribution inefficiencies.Bhusal (2024) These losses waste energy and cause financial harm to utilities and the national economy. Poor voltage profiles also lead to equipment failures, shorter appliance lifespans, and dissatisfied customers. It is crucial for the NEA to find practical and cost-effective ways to reduce power losses and improve voltage profiles.Akhtar et al. (2021) This study discusses three possible strategies for reconfiguring the Biratnagar distribution system. The strategies were tested using ETAP software with actual NEA data from 2025.Hanson and Grigsby (2017) The main goal was to track changes in two key areas: active power losses and voltage stability. The results will help NEA compare options and make informed decisions about investments and upgrades.Moshref (2023)

Technical power losses in distribution systems arise from basic electrical effects. The primary source is copper loss (I^2R loss) in conductors and transformers, where the current passing through the resistance produces heat. Because losses increase with the square of the current, reducing current by 10% cuts losses by 19%, so any method that lowers current can help reduce losses.Wang et al. (2016) The conductor resistance depends on the material and size, as shown below: Resistivity (ρ) depends on the material, length (L) adds to the total resistance, and cross-sectional area (A) reduces resistance as it increases. Doubling the cross-sectional area of a conductor approximately halves its resistance, which lowers losses if the current remains the same. Longer feeders increase technical losses. In Biratnagar, the total feeder length is 61.9 km, which contributes to higher losses because the current travels farther. Choosing the right ACSR conductor is important, with types like Dog (300 A), Wolf (405 A), Bear (595 A), and Zebra (730 A), each offering different resistance levels.Mansor (2022)

Aging ACSR infrastructure presents specific problems. Over the decades, oxidation and corrosion have increased conductor resistance beyond the original levels. The NEA's Distribution System Upgrade and Expansion Project (DSUEP) replaced 290 km of conductors, thereby reducing losses by approximately 15% and increasing system capacity. This demonstrates that large-scale conductor upgrades are technically and practically feasible in Nepal. Lowering feeder impedance reduces losses and improves voltage profiles. The voltage drop along distribution feeders follows the aforementioned relationship. Here, the current (I) interacts with the resistance (R) and reactance (X), whereas the power factor angle (ϕ) affects these interactions. Long feeders, high currents, and poor power factors can cause voltage drops, especially at distant points in the network. If the voltage falls below 95% of the minimum standard, equipment performance suffers. Motors lose torque, making it more difficult to start and run loads.Acharya and Tewari (2019) Fluorescent lights become dimmer below 95% voltage, thereby affecting work environments. Electronic devices with voltage-sensitive parts also have much shorter lifespans at low voltages.KC and Regmi (2019)

Poor service quality leads to lower satisfaction, more appliance failures, and less competitive industrial facilities for consumers. Manufacturers needing a steady power supply may move to areas with better voltage control, which can hurt local economic growth and reduce tax income. Distributed generation (DG), especially solar systems, changes how power flows in a network. Traditional radial networks transmit power in one direction from a central source to users. DG systems generate power close to where it is consumed; therefore, less power needs to travel through the main feeders. Loss reduction is non-linear; moderate levels of DG provide the best results without causing problems, such as voltage rise, protection issues, or islanding risks.

Studies have shown that having 20-25% power from the DG strikes a good balance between reducing losses and maintaining system stability. Nepal has strong solar potential, with an average sunlight of 4.5-5.5 kWh/m^2/day nationwide. Biratnagar receives approximately 4.5

kWh/m^2/day, making rooftop solar systems practical. There have been successful examples in Nepal. The Soaltee Hotel in Kathmandu runs a 506 kW rooftop solar system that produces approximately 600 MWh per year, covering 70% of its energy needs. Similar projects in Pokhara's commercial sector have demonstrated that urban rooftop solar systems work well. Upgrading conductors means replacing old ones with higher-capacity ACSR types that have larger cross-sectional areas and better electrical properties. Nandish et al. (2023) This can cut resistance by 30-45% when moving to the next ACSR type and boost ampacity by 60-112% when upgrading by two types. It also lowers voltage drops and makes the system more reliable by reducing thermal stress. The main benefit is lower conductor resistance, which reduces I^{2}R losses. Nepal has demonstrated that this is possible: the DSUEP replaced 290 km of conductors in difficult mountain areas, costing NPR 350, 000-500, 000 per kilometer. Major upgrades typically take 3-6 months.

The reactive power flow increases the current and I^{2}R losses but does not deliver useful active power. It originates from inductive loads, such as motors and transformers, and becomes a problem when the network power factor drops below 0.85–0.95. Reducing the reactive current lowers the total system current, which in turn reduces I^{2}R losses, regardless of the resistance. Capacitor banks generate reactive power locally; therefore, a lower reactive current must flow through the conductors. The placement of capacitors significantly affects performance. Installing them at 11 kV near load centers provides reactive power support where voltage drops are most severe. The voltage increase provided by the capacitor helps reduce voltage drops further down the line, supporting end users. Placing capacitors at a 33 kV substation provides bulk compensation but is less effective for remote 11 kV buses, where most loads are concentrated. NEA studies found that optimized capacitor placement improved power factors from 0.80-0.85 to over 0.95, with matching reductions in losses.Kuhi et al. (2016); Ali et al. (2017)

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature, Section 3 explains the methodology, Section 4 presents and analyzes the findings, and Section 5 offers final recommendations.

2. Methodology

This study was carried out to analyses the performance of the 33 kV radial distribution network supplied from the Duhabi Grid. The main purpose was to reduce power loss and improve voltage stability. Three improvement methods were studied: distributed generation integration, conductor upgrading, and capacitor placement. The system was simulated using real data from the Nepal Electricity Authority (NEA) and the ETAP software.

A. System Modeling and Data Collection

This study considers a 33 kV radial distribution network supplied by the Duhabi grid (132/33 kV). The network supplies electricity to three substations: Rani, Tanki, and Katahari. Technical information, such as conductor impedance, transformer rating, circuit breaker data, and 2025 load profile data, was collected from the NEA. The total feeder length was 61.9 km. The Rani feeder was 26 km long and used a Wolf-type ACSR conductor with a current rating of 405 A. The Tanki feeder was 7 km long and used a Bear-type ACSR conductor with a current rating of 595 A. The Katahari feeder was 28.9 km long and used a Dog-type ACSR conductor with a current rating of 300 A. Different conductor impedance values were also included in the model. Resistance and reactance values for Wolf, Bear, Dog, and Zebra conductors were taken from real technical specifications. The ETAP model was developed using NEA system data, such as transformer ratings, feeder parameters, and load distribution information. The base-case simulation was verified by comparing the results with real operating data from the NEA. A simplified single-line diagram of the Biratnagar distribution system supplied by the Duhabi grid is shown in Figure. 1.

B. ETAP Model Development and Validation

A power flow analysis was performed using ETAP software version 21.0. The distribution-network model included a 132/33 kV Duhabi grid transformer, 33 kV feeders, three 33/11 kV transformers, and 11 kV distribution circuits. The Newton–Raphson method was used for the load-flow analysis with a very small error tolerance value of 0.0001 per unit. Model validation was performed by comparing the simulation results with real NEA system data under the same load conditions. The base-case simulation showed a total power loss of approximately 5.155 MW, which is very close to the value reported by the NEA. The difference was less than 0.5%. This confirmed that the model was accurate and could be used for further studies.

3.3 Cases Studies

Four operating conditions were investigated in this study.

Case 0 - Base Case

This case represents an existing distribution system without any modifications. It was used as a reference for comparison with other cases.

Case 1 - DG Integration

Rooftop solar photovoltaic (PV) systems with a total capacity of 16.5 MW were connected to the network. This corresponds to approximately 25% DGEP in the system. The DG capacity was calculated as follows:

- Rani substation: 5.5 MW
- Tanki substation: 7.0 MW
- Katahari substation: 4.0 MW

The system efficiency was assumed to be 85%. This includes inverter and wiring losses, as well as dust effects on solar panels.

Case 2 - Conductor Upgrading

In this case, the old conductors were replaced with higher-capacity ACSR conductors.

- Rani feeder:Wolf conductor was replaced with Zebra conductor (26 km). This reduced resistance by about 55 per cent and increased current capacity from 405 A to 730 A.
- Tanki feeder: : Bear conductor was replaced with Zebra conductor (7 km). The resistance was reduced by approximately 59%, and the current capacity increased from 300 A to 595 A.
- Katahari feeder: : Dog conductor was replaced with Bear conductor (28.9 km). Resistance was reduced by about 59%, and current capacity increased from 300 A to 595 A.

Case 3 - Capacitor Placement

Case 3I: Two capacitor placement cases were studied. Each case used shunt capacitor banks with a total rating of 15 MVAR.

Case 3II: Capacitors were installed at 33 kV buses, including the Duhabi grid and substations (total 15 MVAR).

The capacitors were switched on and off based on the voltage level. The capacitors were connected when the bus voltage was below 95% and disconnected when the voltage was above 98%.

D. Performance Evaluation

The system performance was measured using two indicators.

Power Loss Reduction

The loss reduction percentage was calculated by comparing the modified system loss with the base-case loss.

Voltage Profile Improvement

The voltage improvement was measured by comparing the bus voltage levels before and after applying the improvement methods. These indicators were used to verify the effectiveness of DG integration, conductor upgrading, and capacitor placement in improving the distribution system performance.

3. Results and Discussion

3.1 Base Case Analysis: Existing System Performance

A base-case analysis was performed to understand the current condition of the distribution system before applying any improvement methods. The load-flow analysis was performed using the ETAP software under peak-demand conditions of 37.86 MVA. The simulation results showed that the total active power loss was 5.155 MW, which was approximately 13.6% of the total supplied power. The lowest bus voltage was 94.2%, which was below the acceptable voltage limit. The power factor of the system is 79.60%. The feeder currents were close to the thermal limit. The Rani feeder carried a current of 405 A, which is close to its capacity limit. The Tanki feeder current was 365 A, which is close to its maximum capacity of 595 A. The Katahari feeder current was 298 A, which is near its thermal limit. These results indicate that the system has a very small margin for future load increases. The key performance indicators of the base case are summarized in Table 1. The voltage profile across the major buses in the base case is illustrated in Figure. 2, which shows that several buses operate near or below the acceptable voltage threshold.

3.2 Case 1: Distributed Generation Integration

Rooftop solar photovoltaic systems with a total capacity of 16.5 MW were connected to the distribution network. This represented approximately 25% DG penetration. After DG integration, the system performance improved. A detailed comparison of the system parameters before and after DG integration is presented in Table 2. Active power loss was reduced by 31.2%. This occurred because part of the load demand was supplied locally by the DG units. Consequently, the current flowing from the main grid decreased. Because distribution losses mainly depend on the current, reducing the current directly reduces I^2R losses. The current in all three feeders was reduced by approximately 25%. The minimum system voltage improved to 95.9%. This improvement occurred because the reduced current flow resulted in a smaller voltage drop along the feeders. DG power injection near the load centers also helped maintain voltage levels. The system power factor improved to 84.32% because the reactive current requirement decreased. The improvement in bus voltages after DG installation is illustrated in Figure. 3, which clearly shows the enhancement in voltage levels across the network.

3.3 Case 2: Conductor Upgrading

In this case, the existing conductors were replaced with higher-capacity ACSR conductors. The conductor upgrade produced the highest loss reduction among all the studied methods. The total active power loss decreased by 46.5%. This improvement primarily occurred because the resistance of the feeders was reduced. The current flowing in the system remained almost the same as that in the base case because there was no change in the generation or load. However, a reduction in the resistance directly reduces the power loss according to the I^2R relationship. The details of the conductor replacement and associated technical improvements are presented in Table 3.

The Rani feeder showed the highest resistance reduction of about 55% after upgrading from Wolf to Zebra conductor. The Tanki feeder exhibited approximately a 25% resistance reduction. The Katahari feeder offered the greatest benefit, with the Dog conductor upgraded to a Bear conductor, resulting in approximately a 59% reduction in resistance. The minimum bus voltage improved to 96.1% because a lower resistance and reactance reduced the voltage drop along the feeders. The different types of ACSR conductors used in this study are illustrated in Figure. 4, which shows the Wolf, Bear, Dog, and Zebra conductor configurations. The voltage drop is related to the line resistance, reactance, current, and power factor. Upgrading the conductors also improved the system capacity. The Rani feeder could carry approximately 80% more current before reaching its limit of 730 A. The Tanki feeder had approximately 59% additional current margin. The Katahari feeder showed a significant improvement in capacity, as the current margin increased significantly. These improvements help the system handle future load growth of approximately 6–9% per year. A comparison of the overall system performance between the base case and the upgraded conductor case is summarized in Table 4.

3.4 Case 3: Capacitor Bank Placement

3.4.1 Capacitor Placement at 11 kV Buses

Capacitor banks with a total rating of 15 MVAR were installed at the 11 kV buses of the Rani, Tanki, and Katahari substations (5 MVAR each). This case resulted in a significant improvement in system performance. Active power loss was reduced by 32.5% because the capacitor banks supplied reactive power locally. This reduced the reactive current flowing through the distribution lines. The total system current decreased because the reactive component of the current was reduced. As losses depend on the square of the current, a reduction in current helped decrease the I^2R losses. The voltage profile improved by 2.7%, the highest among all the studied cases. This improvement occurred because capacitors were installed near the load centers at 11 kV. The improvement in the voltage profile owing to capacitor placement is illustrated in Figure. 5, which compares the base case with the capacitor-compensated cases. Local reactive power support directly improved the voltage at consumer buses. The performance results for this case are summarized in Table 5.

3.4.2 Capacitor Placement at 33 kV Buses

In this case, 15 MVAR capacitor banks were installed at the 33 kV level, including the Duhabi grid and its substations. A detailed performance comparison for this case is presented in Table 6. This case also reduced the power loss by 28.4 %, which is similar to that of the 11 kV capacitor case. This demonstrates that loss reduction is mainly dependent on the amount of reactive power compensation. However, the voltage improvement was only 1.0%. The main reason for this is that the capacitors installed at the 33 kV level must supply reactive power through a long feeder impedance to reach remote 11 kV loads. Therefore, the voltage support at consumer buses was weaker than that provided by 11 kV capacitor placement.

3.5 Overall Technical Comparison

A comprehensive comparison of all improvement strategies is presented in Table 7. The results indicated that different strategies are useful for different performance objectives. The conductor upgrade resulted in the highest loss reduction of 46.5%. This method directly reduces resistance and power loss. Placing the capacitor at the 11 kV level yielded the best voltage improvement, with a minimum voltage of 96.9%. The distributed generation integration provided balanced performance, with a 31.2% loss reduction and a 95.9% voltage level. This method is useful when renewable energy integration is also an important objective. Overall, conductor upgrading is optimal for loss reduction, whereas capacitor placement near load centers is more effective for voltage improvement. Distributed generation provides a balanced technical solution for modern distribution systems. A practical decision-making comparison considering technical and implementation factors is summarized in Table 8, which can assist utilities, such as the NEA, in selecting the most appropriate strategy for system improvement.

4. Table and Figure

Table 1: Base case key performance indicators

Performance Indicator	**Value**	**Remarks**
Total Active Power Loss	5.155 MW	Represents significant technical losses
Minimum System Voltage	94.20%	Far below acceptable standard
Grid Power Factor	79.60%	Indicates poor reactive power management

Table 2: DG case performance comparison

Parameter	**Base Case**	**DG Case**	**Change**
Power Loss	5.155 MW	3.549 MW	-31.2%
Minimum Voltage	94.20%	95.90%	+1.7 points
Rani Feeder Current	405 A	302 A	-25.4%
Tanki Feeder Current	365 A	274 A	-24.9%
Katahari Feeder Current	298 A	223 A	-25.2%
System Power Factor	79.60%	84.32%	+4.72 points

Table 3: Conductor upgrade and electrical improvement of three feeders

Feeder	**Original Conductor**	**New Conductor**	**Length (km)**	**Ampacity Increase**	**Resistance Reduction**
Rani	Wolf	Zebra	26	405→730 A (+325 A)	55%
Tanki	Bear	Zebra	7	595→730 A (+135 A)	25%
Katahari	Dog	Bear	28.9	300→595 A (+295 A)	59%

Table 4: Performance results after conductor upgrade

Parameter	**Base Case**	**Conductor Case**	**Change**
Power Loss	5.155 MW	2.757 MW	-46.5%
Minimum Voltage	94.20%	96.10%	+1.9 points
Rani Feeder Current	405 A	405 A	No change
Tanki Feeder Current	365 A	365 A	No change
Katahari Feeder Current	298 A	298 A	No change
Rani Feeder Ampacity Margin	0 A	325 A	+325 A (+80%)
Tanki Feeder Ampacity Margin	230 A	365 A	+135 A (+59%)
Katahari Feeder Ampacity Margin	2 A	297 A	+295 A (+14,750%)

Table 5: Performance results for 11kV capacitor case

Parameter	Base Case	11kV Capacitor Case	Change
Power Loss	5.155 MW	3.483 MW	-32.5%
Minimum Voltage	94.20%	96.90%	+2.7 points
System Reactive Power Flow	High	Reduced	-35%
System Power Factor	79.60%	89.45%	+9.85 points

Table 6: Performance results for 33kV capacitor case

Parameter	Base Case	33kV Capacitor Case	Change
Power Loss	5.155 MW	3.703 MW	-28.4%
Minimum Voltage	94.20%	95.20%	+1.0 points
System Reactive Power Flow	High	Reduced	-30%
System Power Factor	79.60%	87.52%	+7.92 points

Table 7: Overall technical comparison of all cases

Case	Power Loss	Loss Reduction	Minimum Voltage	Technical Strength
Base Case	5.155 MW	0%	94.20%	Benchmark
DG Integration	3.549 MW	31.2%	95.90%	Balanced improvement
Conductor Upgrade	2.757 MW	46.5%	96.10%	Maximum loss reduction
11kV Capacitors	3.483 MW	32.5%	96.90%	Best voltage support
33kV Capacitors	3.703 MW	28.4%	95.20%	Bulk compensation

Table 8: Overall technical comparison of all cases based on selection criteria

Selection Criteria	Conductor Upgrade	11kV Capacitors	DG Integration	33kV Capacitors
Loss Reduction	Best (46.5%)	Good (32.5%)	Good (31.2%)	Adequate (28.4%)
Voltage Support	Good (96.1%)	Best (96.9%)	Good (95.9%)	Weak (95.2%)
Ampacity Margin	Excellent	None	Minor	None
Future Demand Growth	Supports 6–9%	Limited	Limited	Limited
Implementation Speed	3–6 months	1–3 weeks	6–12 months	1–3 weeks
Investment Level	High	Medium	Medium	Medium-Low
Permanence	40+ years	15–20 years	25–30 years	15–20 years

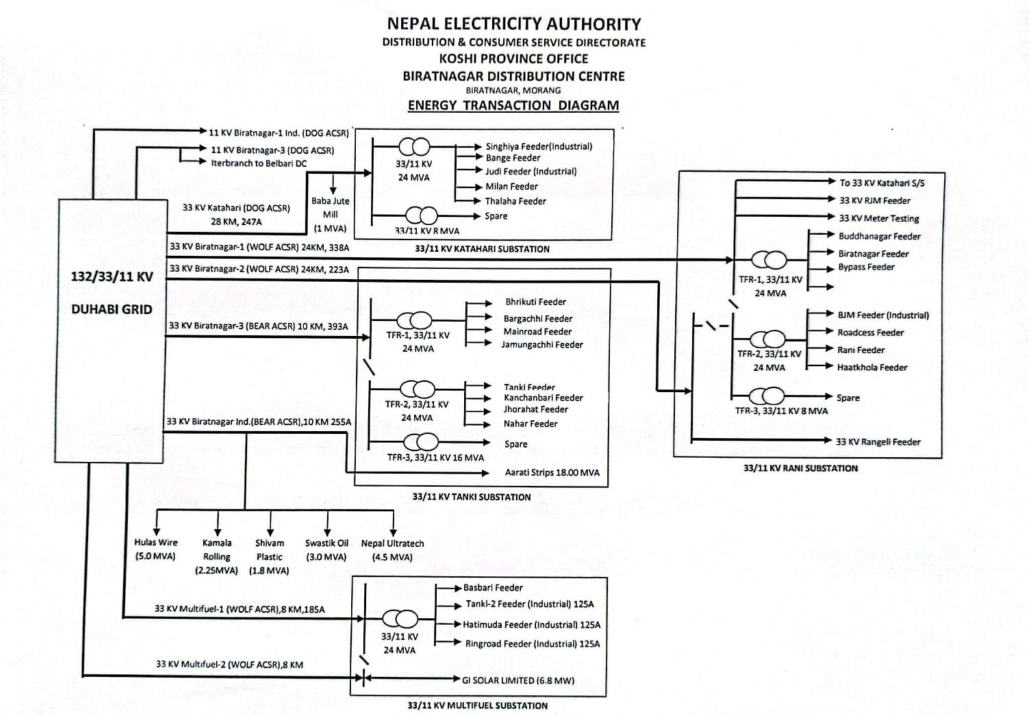

Figure 1: Single line Diagram from Dhabi Grid to Biratnagar Substation

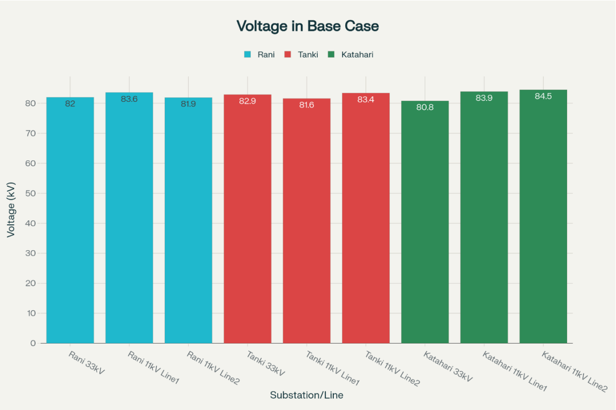

Figure 2: Voltage Profile Across Key Buses in Base Case

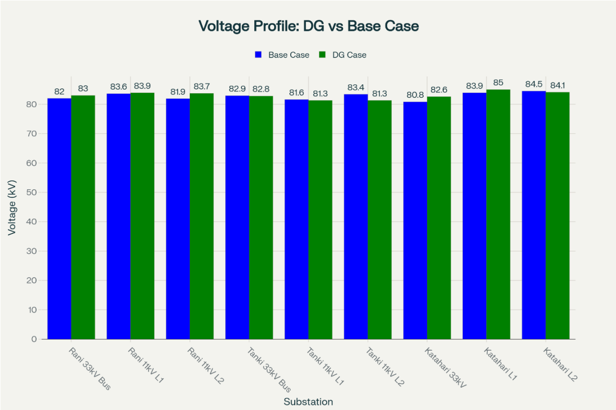

Figure 3: Voltage Profile Improvement Across Key Buses in DG Case

Figure 4: Voltage Profile Improvement Across Key Buses in Conductor Upgrade Case

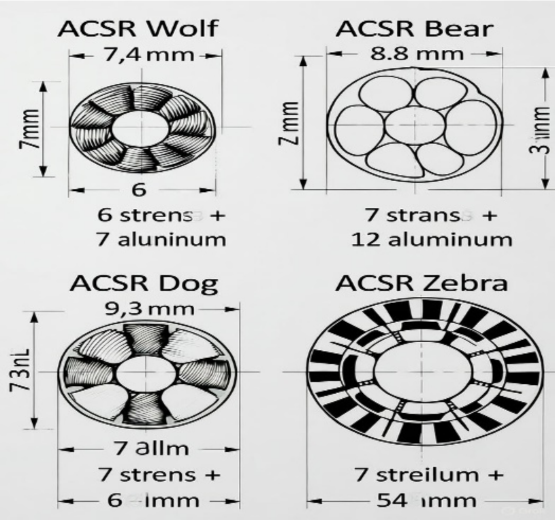

Figure 5: Voltage Profile Improvement Across Key Buses in Capacitor Case

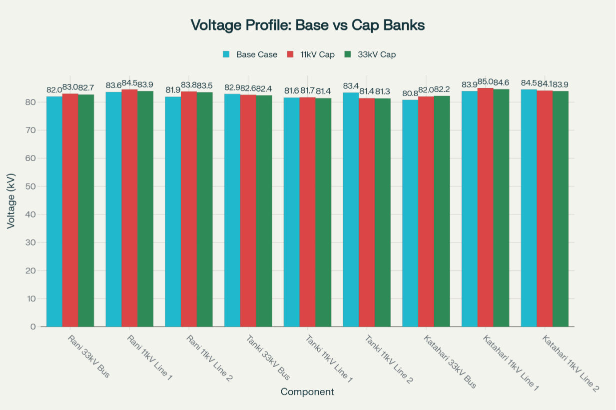

Figure 6: Comparison of voltage profiles across key buses (base vs. 11 kV cap vs. 33 kV cap)

5. Conclusion and Recommendation

This study investigated technical strategies to improve the operational performance of a Biratnagar distribution system. Four approaches were analyzed: conductor upgrading, capacitor bank installation at 11 kV and 33 kV buses, and distributed generation (DG) integration. The analysis focused on power loss reduction, voltage profile, and power factor improvement. Conductor upgrading provided the greatest reduction in technical losses, decreasing system losses from 5.155 MW to 2.757 MW (46.5% reduction). The upgraded conductors increased the feeder capacity and improved the voltage profile to 96.1%, supporting future load growth. Capacitor banks at 11 kV buses provided optimal voltage support, increasing the minimum bus voltage to 96.9% and reducing power loss by 32.5%. This improved the system power factor from 79.60% to 89.45%, thereby enhancing the efficiency and equipment performance. Distributed generation integration using rooftop photovoltaic systems (16.5 MW) reduced system losses by 31.2% and improved the minimum voltage to 95.9%, while contributing to renewable energy development. Capacitor banks at 33 kV buses achieved a 28.4% loss reduction and improved the power factor to 87.52%, offering a lower-cost, quick-implementation option. The Nepal Electricity Authority (NEA) can select strategies based on priorities: conductor upgrading for maximum loss reduction, 11 kV capacitors for voltage quality, DG for renewable energy, and 33 kV capacitors as a cost-effective option.

6. Author's declaration

The authors declare no conflicts of interest regarding the publication of this research paper. All contributors agreed to the final draft of the manuscript.

7. Declaration of the conflict of interest

The authors declare that there are no irreconcilable circumstances. All authors contributed to the preparation of the final manuscript.

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