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IMPROVING THE ENERGY EFFICIENCY OF A POWER DISTRIBUTION NETWORK BY LOSS REDUCTION: A CASE STUDY IN RURAL 11 KV FEEDER

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ABSTRACT:

There are inherent losses in transmission and distribution of electrical energy from the generating stations to the ultimate consumer. In this study three different distribution systems viz. IEEE 10 Bus, IEEE 33 Bus Radial Distribution System and a practical Nepalese rural Distribution System are undertaken, and load flow study is carried out to identify the technical loss and various reinforcement techniques are implemented for loss reduction. The technical loss evaluated for 10 Bus, 33 Bus and practical feeder are 5.96%, 5.37% and 12.18% respectively. Capacitor Placement technique was used to study the loss reduction on the standard distribution system which reduced the loss to 5.32% and 3.98% respectively on the 10 Bus and 33 Bus system. Various reinforcement techniques: Conductor Upgradation, Capacitor Placement, Solar PV Integration, Combination of Conductor upgradation & Capacitor Placement; and combination of Solar PV integration and Capacitor Placement were studied on the practical feeder. These methods reduced the 12.18% loss at base case to 11.76%, 8.44%, 8.10%, 7.43%, and 4.22%. This study finds Capacitor Placement to be the most suitable method for loss reduction among the methods studied and similarly combination of conductor upgradation and capacitor placement is also found to be effective solution for loss reduction and efficiency improvement. Other methods undertaken for study are not found to be as effective due to their high investment cost but low returns in terms of loss reductions.

KEYWORDS: *loss, capacitor placement, conductor upgradation, IEEE Bus, efficiency*

1. INTRODUCTION

The distribution of energy inevitably leads to losses when it is transferred from substations to consumers, resulting in significant revenue loss due to missed opportunities for providing service. It is imperative for utilities to prioritize reducing these losses to acceptable levels. Data from [1] highlights a substantial portion of South Asia's electricity being lost during transmission and distribution networks. In Nepal, the Nepal Electricity Authority (NEA) is responsible for nationwide electricity distribution as the primary state-owned utility. As of Fiscal year 2021/22, Nepal's distribution system consists of 6,620 circuit km of 33 kV, 44,840 circuit km of 11 kV, and 136,595 circuit km of 0.4/0.23 kV. The overall system loss stands at 15.38%, with a distribution system loss of 10.86% for FY 2021/22 [2].

Nepal's power system is grappling with a significant 10.86% loss in the distribution system [2]. These energy losses represent a missed opportunity for generating revenue, underscoring the importance of minimizing these losses to the greatest extent possible. To address this issue, the Nepal Electricity Authority (NEA) has implemented various measures, including the installation of new distribution transformers, discontinuation of service for consumers with unpaid bills, combating theft by sealing meters, confiscating equipment, and preventing illegal connections [2], [3]. NEA's efforts have primarily focused on reducing non-technical losses, but it should also concentrate on decreasing technical losses through the adoption of various techniques such as capacitor placement, reconductoring, voltage upgrades, system reconfiguration, and integration with distributed generation sources[4].

One specific example is the 11 kV Padajungi Feeder of the Gauradaha Distribution Center, which spans 136.4 km and has a maximum feeder load of 300 A [2]. This feeder supplies power to various regions in Eastern Nepal, including the Gauradaha Municipality, Gaurigunj Rural Municipality, and Kamal Rural Municipality in the Jhapa District. Since these areas rely heavily on agriculture, inductive motors for irrigation purposes are commonly used. These inductive loads significantly contribute to voltage drops, resulting in inadequate voltage supply for household appliances. In the Fiscal year 2078/79, the Gauradaha DC recorded a loss percentage of 11.88% [2], [3].

Therefore, this study aims to conduct a load flow analysis in both a 10 Bus Test system and a 33 Bus Test system with a radial distribution configuration. It also applies the same methodology to a practical feeder, the 11 kV Padajungi Feeder in Nepal. The goal is to implement various techniques and combinations thereof to reduce losses and enhance efficiency in the distribution system.

2. LITERATURE REVIEW

Losses within a distribution network can be divided into two distinct categories, namely technical and non-technical losses [5]. Technical losses can further be subcategorized into variable losses and fixed losses. Variable losses are directly associated with the flow of electrical current and primarily occur within copper-based components such as lines, cables, and transformers. These losses are commonly referred to as copper losses and are directly proportional to the power being distributed throughout the network [5].

There exists a wide array of methods aimed at mitigating losses within distribution systems. These methods encompass activities such as capacitor placement, reconductoring, voltage upgrades, monitoring the load on transformers, and system reconfiguration [4]. Notably, feeder reconfiguration, the strategic placement of capacitors, and the integration of distributed generation sources have all been extensively researched as effective means of reducing losses at the distribution level.

The study [6] aims to reduce power losses by using feeder bifurcation and reconductoring techniques. [7] introduces a new algorithm for reconfiguring power distribution systems to reduce operating costs in real-time. Study [8] proposes an algorithm to address the problem of capacitor placement on radial distribution systems. The algorithm considers the cost of capacitors, peak power and energy loss reduction, voltage constraints, and load variations in its formulation. [9] introduces a new swarm intelligence algorithm called Ant Colony Search Algorithm (ACSA) for the optimization of feeder reconfiguration and capacitor placement in distribution systems.[4] concludes the advancement of technology and the shift towards smart grids offer new solutions for reducing these losses, including strategies for reducing technical losses and the use of technologies such as AMI and pre-paid meters to reduce non-technical losses. [10] suggests there has been a growing interest in renewable energy sources lately, leading to an increase in the study of integrating Distributed Generation (DG) into power grids and one of the key benefits of DG is reducing power losses and improving the voltage profile.

Authors in [11] propose a method to analyze the power loss of Tai power distribution systems and the entire power system. The approach involves creating ANN-based models to simplify the analysis of feeder power loss for both overhead and underground feeders. [12] discusses how transmission and distribution (T&D) losses in a distribution utility are typically calculated based on 11 KV feeders, which serve different types of consumers. Literature [13] mentions that the Indian power sector is facing a crisis due to inefficiency and substantial commercial losses and to reverse this trend, drastic measures are required to reduce losses and improve billing and revenue collection efficiency. The paper discusses various technical, commercial, and administrative interventions needed to address these issues. The proposed measures for the Sindhudurg circle in Maharashtra state are quantified, and it was found that losses in the circles would reduce by 12% with an investment that has a payback period of about four years. [14] presents an investigation of a specific 11 kV distribution feeder network in Akure township, Nigeria. The aim of the study was to assess the power distribution problems and propose solutions for the effective use of existing 11 kV feeders for power supply in Nigeria. The paper [15] describes the use of the power loss index method to determine the optimal placement of D-STATCOM in a radial distribution system, to reduce line losses and improve voltage profile.

3. METHODOLOGY

Three feeders with radial configuration :10 Bus, 33 Bus Test Feeders and a practical 11 kV Padajungi Feeder are used in this study. The test feeder is modelled on ETAP and a load flow study is carried out. The same methodology is used for the practical feeder (11 kV Padajungi Feeder) which originates from the 132/33/11 kV Damak (Padajungi) Substation. It is 136.4 km long and has maximum feeder load of 300 A [2]. The area fed are the various places of Eastern Nepal, the Gauradaha Municipality, Gaurigunj Rural Municipality and Kamal Rural. The load and line data of IEEE 10 and IEEE 33 Bus test system is taken from [16] and [17] respectively. The single line diagram is obtained from Nepal Electricity Authority and length of the practical feeder has been obtained with Google Earth. The distribution transformer's location are plotted to find the distance between various bus. The model contains 92 loads from 92 Distribution Transformers of 50, 100, 200 and 300 kVA ratings. The mapping is presented in Figure 1.

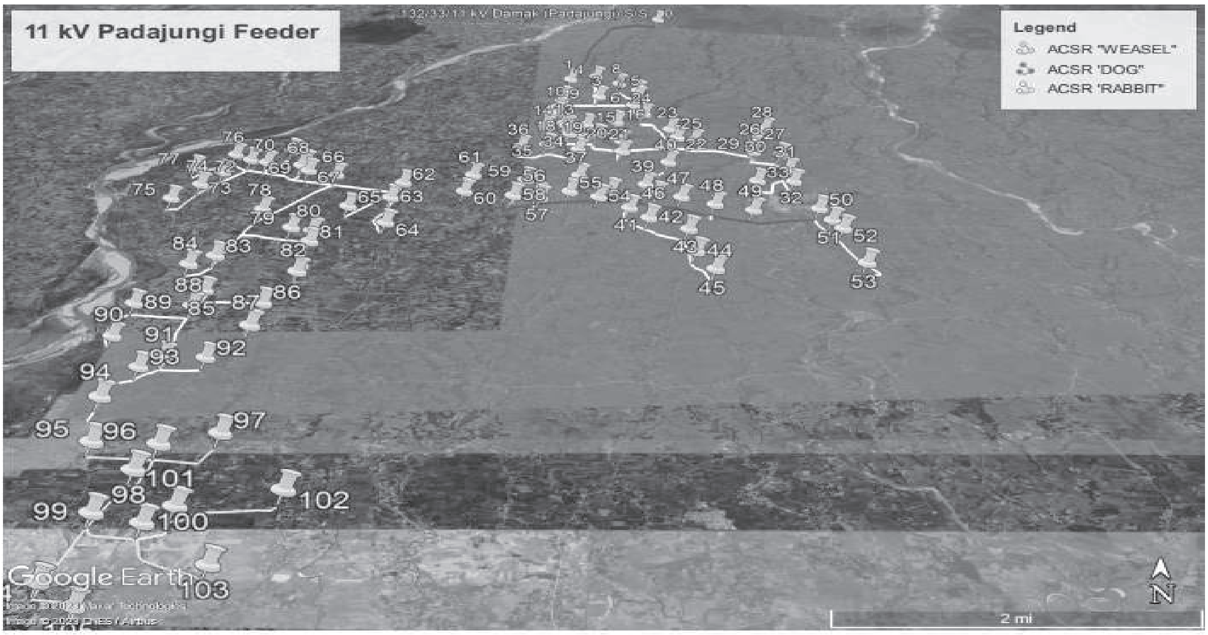

Figure 1 11 kV Padajungi Feeder Mapped in Google Earth

Five different reinforcement methods are undertaken for study in the practical real feeder. Conductor upgradation, capacitor placement, integration with solar PV is individually studied by implementing on the base case scenario. A combined method of conductor upgradation with capacitor placement and Solar PV integration with capacitor placement is also studied.

A total of 12.43 km of WEASEL conductor has been upgraded to RABBIT and 48.34 km has been upgraded from RABBIT to DOG. Five capacitor banks are placed at Bus 22,37,49,66,91. A total of 5 MVAR capacitor banks are placed, and the capacitor bank supplies the reactive power to the system. The PV Array editor in ETAP is used to integrate a Solar PV to the distribution system. The technical specification of the Solar PV is specified in [18]. The Solar PV system consists of 4500 Solar panels, with an output of 239.7 W/Panel connecting 30 panels in series and 150 panels in parallel to obtain 1078.6 kW DC output. Bus 85 with Latitude 26°31'57.81"N and Longitude 87°39'48.87"E is selected for PV integration.

4. RESULT AND DISCUSSION

The load flow of IEEE 10 Bus test system shows total active load of 13.15MW and active loss 0.784 MW. Bus 2,3,4,5,6 is selected as candidate nodes and a total of 6000 kVAR is installed which reduces the loss to 0.695 MW. Similarly, the load flow of IEEE 33 Bus Test system shows total active load of 3.926MW and active loss 0.211 MW. Bus 9, 15,16,29,31 is selected as candidate nodes and a total of 2400 kVAR is installed which reduces the loss to 0.154 MW.

Figure 2 shows the per unit Bus voltage Before and after the capacitor placement. The lowest voltage value is 0.904 p.u. before the capacitor placement. The capacitor bank placement at various bus which boosts the voltage keeping the minimum bus voltage 0.947 p.u.

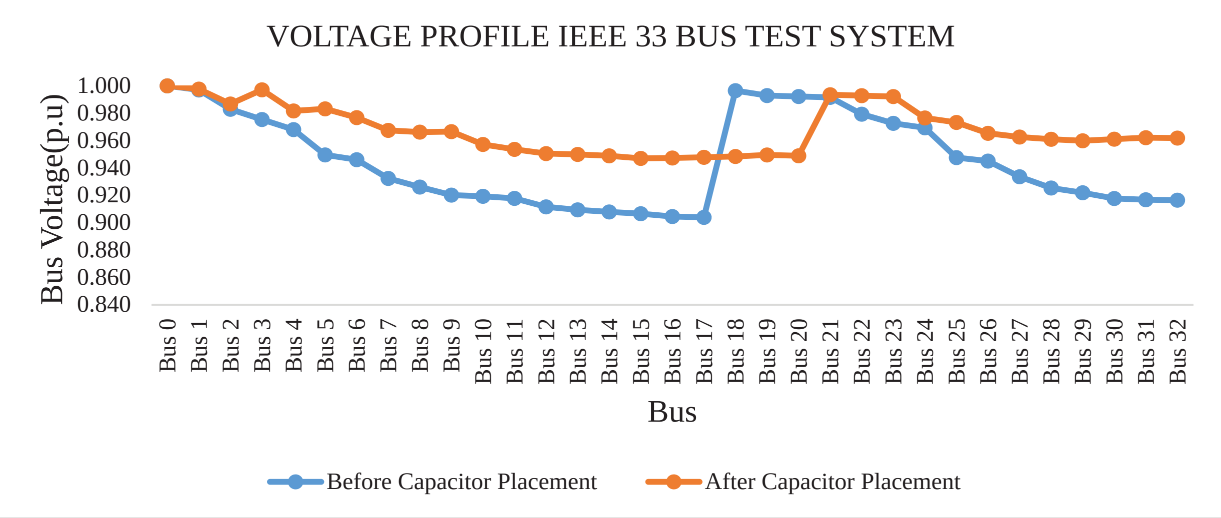

Figure 2 Bus Voltage Comparison of IEEE 33 Bus System Before and After CP

The load and line data of 11 kV Padajungi Feeder is calculated from the lengths calculated by plotting various distribution transformers. Load flow is carried out and ETAP shows an active load of 3.359 MW and active loss of 0.409 MW resulting to 12.18% loss. Various reinforcements techniques are implemented on the base case and Table 1 shows the obtained results.

Table 1 Loss Summary

Methods	Bus	Loads	Load-MW	Load-MVAR	Generation-MW	Loss-MW	% Loss
Base Case	106	92	3.35	2.32	3.35	0.409	12.18
Conductor Upgradation	106	92	3.35	2.33	3.35	0.394	11.76
Capacitor Placement	106	92	3.39	0.173	3.39	0.287	8.44
Conductor Upgradation and Capacitor Placement	106	92	3.39	0.16	3.39	0.275	8.1
Solar PV Integration	106	92	3.27	2.173	3.27	0.243	7.43
Solar PV Integration and Capacitor Placement	106	92	3.34	-0.129	3.34	0.141	4.22

Table 1 shows the loss summary at various cases studied. At base case the active load is 3.35 MW and loss is 0.409 MW resulting in 12.18% loss. The loss is reduced to 0.394 MW after conductor upgradation. Similarly, the capacitor placement in the base case reduces the loss to 0.287 MW. Due to capacitor placement the active load slightly increases to 3.39 MW. After combination of conductor upgradation and capacitor placement is introduced, the active loss reduces to 0.275 MW, and as Solar PV is integrated alone it reaches 0.243 MW. And after capacitor placement and solar PV integration the active loss reduces to 0.141 MW.

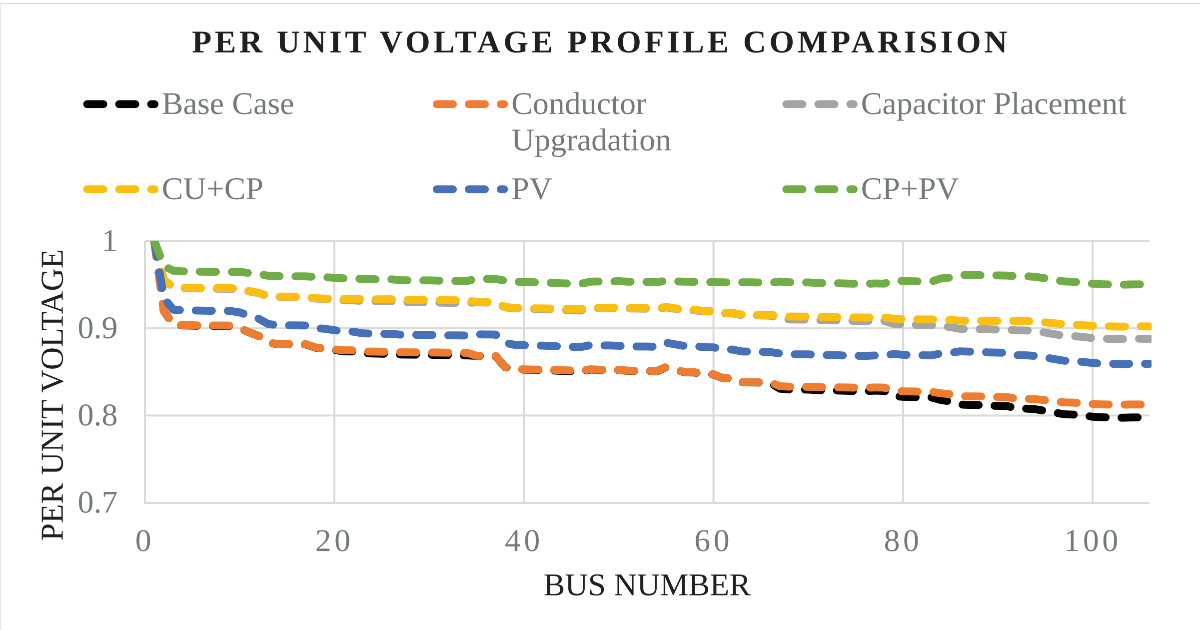

Figure 3 Per Unit Voltage Profile Comparison

Figure 3 shows the per unit voltage at various buses. The minimum p.u. voltage at Base case is 0.80. After conductor upgradation there is a negligible change in the minimum p.u. voltage and is 0.81. After capacitor placement it rises to 0.89 p.u. Similarly, after combination of conductor upgradation and capacitor placement is introduced the minimum p.u. voltage is 0.90, and as Solar PV is integrated alone the minimum voltage is 0.86 p.u. and after capacitor placement and solar PV integration the minimum voltage is 0.95 p.u. Hence, through the introduction of various methods the minimum voltage can be increased and brought to a standard value.

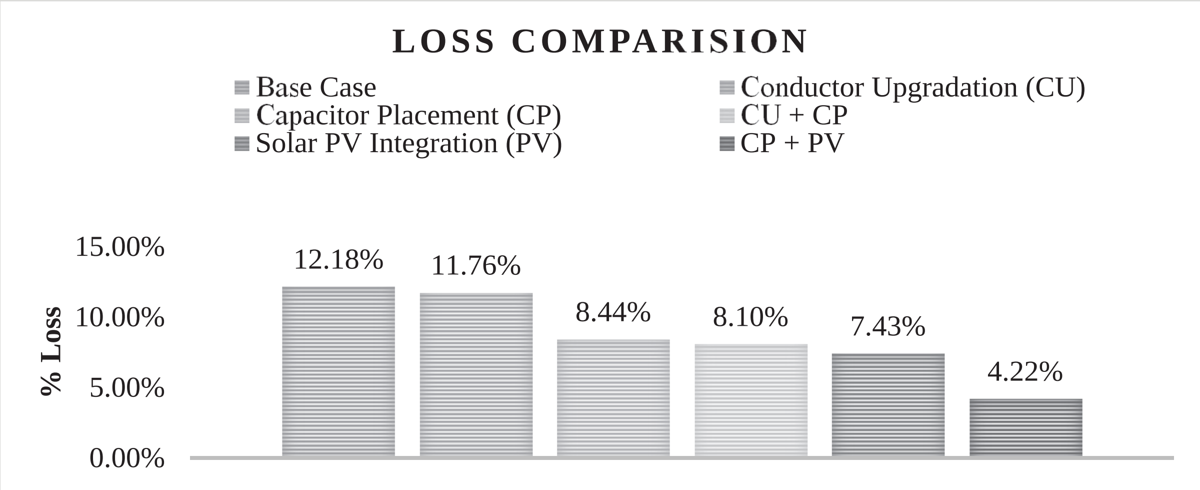

Figure 4 Loss Comparison

Figure 4 shows the percentage loss obtained in the various cases. At the Base case scenario, the loss percentage is 12.18% which gradually is decreased as introduction of various method. In this study Capacitor placement and Solar PV integration jointly reduces the loss to 4.22%

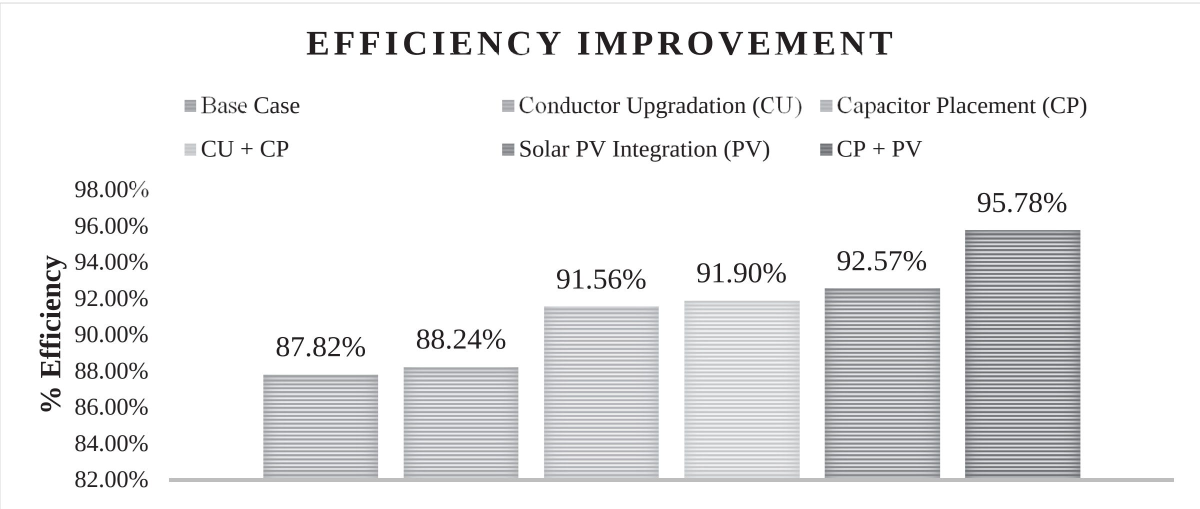

Figure 5 Efficiency Improvement

Figure 5 shows the efficiency of the distribution network. The existing efficiency was 87.82 % which was increased to 95.78% by use of various reinforcement techniques. It can be observed that through the introduction of various reinforcement techniques the efficiency of the power distribution network can be increased.

4.1 Financial Analysis

A) Considerations:

ACSR DOG Conductor: Rs. 1,17,640 /km

ACSR RABBIT Conductor: Rs. 81,840 /km

Capacitor Cost/ kVAR : Rs. 1056 (1$ = Rs. 132) [19]

Solar PV / kW: Rs. 73637.06 [20]

Revenue per kWh: Rs. 9.72[3]

B) Energy Loss Calculation

The energy loss of the network can be estimated from the Loss Load Factor (LLF) method using the following relations [21]:

$$Energy\ Loss = Power\ Loss * Time * LLF$$

And $$LLF = a * (Load\ Factor) + b * (Load\ Factor)^2$$

Where a= 0.2 and b =0.8

Using above assumptions and relations the financial analysis evaluates Annual Energy loss, Annual Revenue loss, Annual Savings that can be achieved, cost per kW Loss reduction and ratio of savings to cost and is tabulated in Table 2

Table 2 Financial Analysis

Method	Base Case	Conductor Upgradation (CU)	Capacitor Placement (CP)	Conductor Upgradation + Capacitor Placement (CU+CP)	Solar PV Integration (PV)	Capacitor Placement + Solar PV Integration (CP+PV)
Cost (NPR)	-	6,703,988.80	5,280,000.00	11,983,988.80	79,424,932.92	84,704,932.92
Load Factor	0.5	0.5	0.5	0.5	0.5	0.5
Loss Load Factor (LLF)	0.3	0.3	0.3	0.3	0.3	0.3
Loss (kW)	409	394	287	275	243	141
Energy Loss (Mwh)	1074.85	1035.43	754.24	722.70	638.60	370.55
Annual Revenue Loss (NPR)	10,447,561.44	10,064,399.04	7,331,173.92	7,024,644.00	6,207,230.88	3,601,726.56
Annual Savings(NPR)	-	383,162.40	3,116,387.52	3,422,917.44	4,240,330.56	6,845,834.88
Loss Reduced (kW)	-	15	122	134	166	268
Cost per kW Loss Reduction (NPR/kW)	-	446,932.59	43,278.69	89,432.75	478,463.45	316,063.18
Saving to Cost Ratio	-	0.06	0.59	0.29	0.05	0.08

Table 2 shows the Financial Analysis considering the investment associated and savings that can be achieved. Various reinforcement techniques: Conductor Upgradation, Capacitor Placement, Solar PV Integration, Combination of Conductor upgradation & Capacitor Placement; and combination of Solar PV integration and Capacitor Placement reduced the 12.18% loss at base case to 11.76%, 8.44%, 8.10%, 7.43%, and 4.22% with investment of 6.7, 5.28, 11.98, 79.42, 84.7 million NPR and annual savings of 0.38, 3.12, 3.42, 4.24, 6.85 million NPR respectively. The Saving to Cost Ratio is found to be 0.06, 0.59, 0.29, 0.05 and 0.08 respectively.

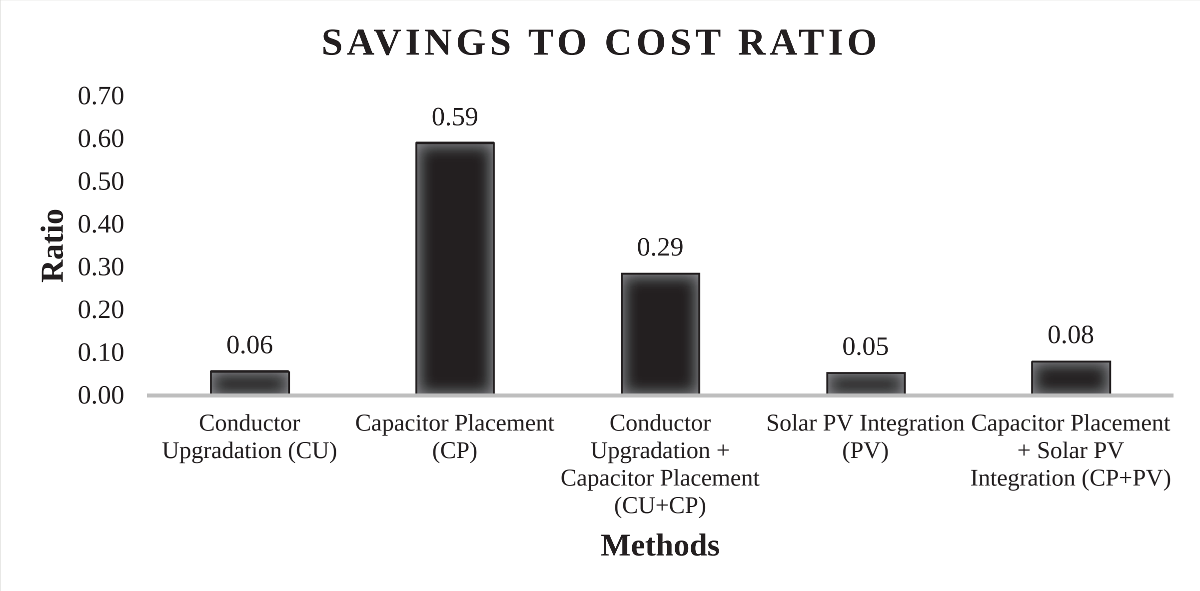

Figure 6 Savings to Cost Ratio

Figure 6 shows the saving to cost ratio of various techniques studied. With respect to the ratio Capacitor Placement is found to be the most suitable method for loss reduction and similarly combination of conductor upgradation and capacitor placement is also an effective solution for loss reduction and efficiency improvement. Other methods undertaken for study are not found to be as effective due to their high investment cost but low returns in terms of loss reduction.

5. Conclusion

Inherent losses occur when electrical energy travels from power plants to the end user through transmission and distribution systems. In this study three different distribution systems viz. IEEE 10 Bus, IEEE 33 Bus Radial Distribution System and a practical Nepalese rural Distribution System are undertaken, and load flow study is carried out to identify the technical loss and various reinforcement techniques are implemented for loss reduction and efficiency improvement.

The technical loss evaluated for 10 Bus, 33 Bus and practical feeder (11 kV Padajungi) are 5.96%, 5.37% and 12.18% respectively. Capacitor Placement technique was used to study the loss reduction on the standard distribution system which reduced the loss to 5.32% and 3.98% respectively on the 10 Bus and 33 Bus system.

Various reinforcement techniques: Conductor Upgradation, Capacitor Placement, Solar PV Integration, Combination of Conductor upgradation & Capacitor Placement; and combination of Solar PV integration and Capacitor Placement were studied on the practical feeder. These methods reduced the 12.18% loss at base case to 11.76%, 8.44%, 8.10%, 7.43%, and 4.22% with investment of 6.7, 5.28, 11.98, 79.42, 84.7 million NPR and annual savings of 0.38, 3.12, 3.42, 4.24, 6.85 million NPR respectively. The respective Saving to Cost Ratio for various methods was found to be 0.06, 0.59, 0.29, 0.05 and 0.08.

Thus, with respect to Savings to Cost Ratio this study finds Capacitor Placement to be the most suitable method for loss reduction among the methods studied and similarly combination of conductor upgradation and capacitor placement is also found to be effective solution for loss reduction and efficiency improvement. Other methods undertaken for study are not found to be as effective due to their high investment cost but low returns in terms of loss reductions.

6. Recommendation

The primary factors contributing to increased technical losses are a fragile system due to limited investments in system reinforcement, extensive rural electrification, unplanned system expansion, ineffective load management, and the improper placement of distribution transformers away from load centres. Technical losses within the power system stem from energy dissipation in transmission, sub-transmission, and distribution equipment and conductors. While it's possible to reduce technical losses to acceptable levels, eliminating them entirely is not feasible.

This study employs short-term measures for reducing technical losses, including reinforcement techniques. Additional measures that can be studied are network reconfiguration, preventing insulator leakages, load balancing, enhancing joints and connections, adopting high-voltage distribution systems, and constructing substations.

Furthermore, long-term measures aim to enhance power supply quality, reliability, and loss reduction. These actions involve strengthening and improving the sub-transmission and distribution system in a specific area to meet the expected load demand over the next five years. The traditional approach to network development should be replaced with a strategy that prioritizes technical and reliability requirements, considering economic factors like energy loss expenses, and expansion of the system to accommodate anticipated demand increase at the lowest possible cost.

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