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**Improving the energy efficiency of a Power Distribution Network by Loss  
Reduction: A case study in rural 11 kV Feeder**

**by**

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**A THESIS**

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled "**Improving the energy efficiency of a Power Distribution Network by Loss Reduction: A case study in rural 11 kV Feeder**" submitted by Roshan Khatiwada in partial fulfillment of the requirements for the degree of Masters in Energy System Planning and Management.

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## ABSTRACT

Inherent losses occur when electrical energy travels from power generation facilities to end-users. Several utility companies do not recognize the benefits of modernizing their distribution systems or conducting assessments like load flow analysis to identify technical losses and performance indicators like voltage levels at customer service points. Consequently, these companies persist in running their networks without conducting any technical evaluations regarding energy losses or the quality of supply.

The research objective is to improve the energy efficiency of a Power Distribution Network by Loss Reduction in a rural 11 kV Feeder of Nepal. Various reinforcement techniques for efficiency improvement such as: Conductor upgradation, Capacitor placement, Integration with Solar PV are studied. Combined methods of Conductor upgradation with Capacitor placement and Solar PV with Capacitor placement are also considered. Finally, a financial analysis is done.

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 in ETAP software 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 implemented. 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 0.09, 0.95, 0.46, 0.09 and 0.13 respectively.

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.

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## LIST OF ACRONYMS AND ABBREVIATIONS

DESCO	Dhaka Electric Supply Company Limited
BPC	Bhutan Power Corporation Limited
NEA	Nepal Electricity Authority
KESC	Karachi Electric Supply Company
DG	Distributed Generation
SVC	Static VAR Compensator
STATCOM	STATic synchronous COMpensator
OCP	Optimal Capacitor Placement
ETAP	Electrical Transient Analyzer Program
kV	kilo Volt
A	Ampere
IEEE	Institute of Electrical and Electronics Engineers
PV	Photo Voltaic
GA	Genetic Algorithm
RDS	Radial Distribution System
ANN	Artificial Neural Network
DT	Distribution Transformer
kVA	kilo Volt Ampere
LLF	Loss Load Factor

## CHAPTER ONE: INTRODUCTION

### 1.1 Background

Energy is crucial for a country's economic growth and is present in various forms, but the most important is electrical energy. Human society heavily relies on electrical energy, and it has become a part of daily life. To meet the increasing demand for electrical energy for domestic, commercial, and industrial use, power plants are used to generate electricity in a cost-effective way. Power plants, also known as electric power generating stations, are responsible for delivering electricity to many consumers. The demand for electricity varies among consumers, leading to fluctuations in the load on the power station [1], [2]. Unfortunately, electrical power can't be stored, so the power station must constantly produce electricity to meet the demand. The power is then supplied to consumers through transmission and distribution networks.

Energy distribution results in unavoidable losses when energy is transferred from the substations to consumers. These losses do not generate any revenue for the utility companies and play a significant role in deciding the best plans and operations. Hence, distribution utilities focus on minimizing these losses to meet the industry standards. Losses in a distribution network are categorized into two types: technical and non-technical [1]. Technical losses are further divided into two parts: variable (load) losses and fixed losses. Variable losses are related to the current flow and occur mainly in copper components like lines, cables, and transformers. These losses are referred to as copper losses and are proportional to the power distributed in the network [1].

Fixed losses, also known as no-load losses, are mainly caused by the heat and noise generated in the transformer cores and remain constant as long as the transformer is powered. These losses can be reduced by using high-quality materials in the core, such as special steel or amorphous iron, or by switching off transformers during low demand periods. However, this depends on the network configuration and the ability of the operator to transfer some load to other sources. Non-technical losses, also known as commercial losses, refer to units of electricity that are consumed but not recorded as sales due to reasons such as meter inaccuracies, incorrect meter installation, billing errors, illegal electricity usage, and unread meters [1].

In the paper “Improving Energy Efficiency in South Asia” [3] published by Asian Development Bank with various country's utilities own published statistics around the year 2014-2016 shows a significant portion of the electricity generated in South Asia is wasted within the transmission

and distribution systems. Table 1.1 [3] shows Transmission and Distribution Losses in selected utilities in South Asia.

**Table 1.1 Transmission and Distribution Losses in selected utilities in South Asia[3]**

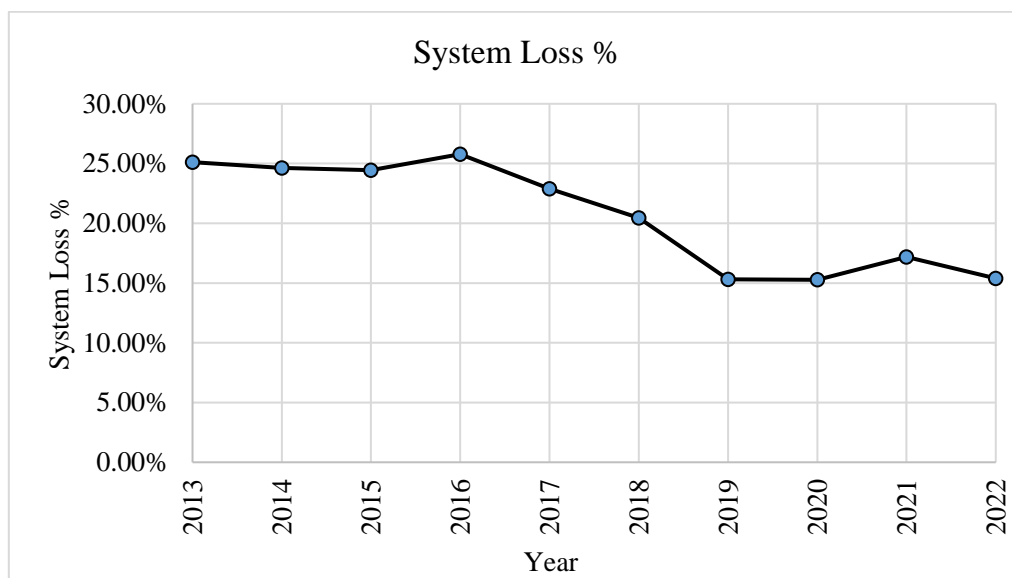
Country	State/Region	Utility	Loss Definition	Operational Area	Losses (%)
Bangladesh	Dhaka Metropolitan region (2014/15)	DESCO	Purchases at 33kV and distributes	Urban and semi urban	8.37%
	Other Cities and Rural Bangladesh			Urban, semi urban, and rural	12%
Bhutan	All Country (2013)	BPC	33kV and below	Urban and rural	4.30%
India	All India		Transmission and Distribution	Whole country	22.69%
Nepal	All country (2014)	NEA	All transmission and distribution	All transmission and distribution	24.44%
Pakistan	All country (2014)	KESC	Transmission and Distribution		15%

The paper [3] mentions many utility companies fail to recognize the benefits of digitalizing their distribution networks and performing load flow analysis to assess technical losses and other performance indicators like voltage levels at customer service points. Consequently, they persist in running their networks without conducting any technical assessments of energy losses or the quality of supply.

In Nepal, the distribution of electricity throughout the country is handled by the Nepal Electricity Authority (NEA), which serves as the primary state-owned electric utility. Founded in 1985, its main objective is to ensure the generation, transmission, and distribution of sufficient, dependable, and cost-effective electricity by overseeing the planning, construction, operation, and maintenance of all power generation, transmission, and distribution infrastructure within Nepal's power grid. [4].

As of Fiscal year 2021/22, the total line lengths of distribution system in Nepal are 6620 circuit km of 33 kV, 44,840 circuit km of 11 kV and 1,36,595 circuit km of 0.4/0.23 kV. The overall system loss is 15.38% and the distribution system loss is 10.86% in FY 2021/22 [5].

Figure 1.1 [4] below shows the total system loss in Nepal's power system. As of year 2022, it is 15.38% out of which 10.86% represents the distribution loss which incorporates technical and nontechnical losses.



**Figure 1.1 Total System Loss of Nepal's power system[4]**

In the literature [6], there is discussion of the factors that lead to the rise of line losses in both the primary and secondary distribution systems, as well as strategies that can be employed to mitigate these losses. These are tabulated in Table 1.2 [6].

**Table 1.2 Factors for high line loss and reduction methods[6]**

Factors contributing to the increase in line losses		Methods for the reduction of line losses	
a.	Inadequate Size of Conductor	a.	HV Distribution System
b.	Feeder Length	b.	Feeder reconfiguration
c.	Location of Distribution Transformers	c.	Reinforcement of the feeder
d.	Low Voltage	d.	Grading of conductor
e.	Use of Over-rated Distribution Transformers	e.	Construction of new substation
f.	Low Power Factor	f.	Reactive-power compensation

Authors in [7] discuss techniques for decreasing losses in the distribution network, which include placing capacitors, upgrading conductors, enhancing voltage levels, monitoring transformer loads, and implementing network reconfiguration. Currently, the distribution system experiences significant losses due to its existing arrangements and setup. The expansion of low-tension lines in urban areas, designed to supply power to scattered loads, follows a radial layout [8]. However, the disorganized arrangement of predominantly agricultural loads in these areas has led to high transmission losses, resulting in a low power factor for the setup. Most Shunt capacitor banks are installed at 33 kV, while their installation at the 11 kV voltage level in the distribution network is rare. To substantially reduce distribution losses, it is crucial to implement capacitor banks at the 11 kV voltage level [8].

Traditional switched capacitor banks enable reactive power compensation in a stepwise manner. On the other hand, Distributed Generators (DG) and devices like SVCs and STATCOMs offer a more flexible and continuous approach to compensation and voltage control [7].

The Capacitor placement objective is to minimize costs while determining the appropriate size and location of the capacitors, which poses an optimization challenge [9]. To address this, an optimization approach should be employed and the ETAP Optimal Capacitor Placement (OCP) module serves as a robust simulation tool designed specifically for this purpose. It efficiently positions capacitors to improve voltage levels and correct power factors, all while keeping costs to a minimum. The user-friendly graphical interface offers flexible control over the capacitor placement process and makes it easy to visualize the outcomes. The precise calculation method automatically identifies the optimal positions and sizes for capacitor banks [2], [9], [10].

## **1.2 Problem Statement**

The power system in Nepal is facing a 10.86% loss in the distribution system [5]. As the energy which is lost could have generated revenue so the loss should be minimized to the lowest possible extent. The Nepal Electricity Authority (NEA) has taken steps to reduce these losses through measures such as installing new distribution transformers, disconnecting lines for consumers who have not paid their dues, controlling theft by resealing meters, seizing equipment, and preventing hooking activities [4], [5].

The activities conducted by NEA are responsible for reducing the non-technical losses so it must also focus on reducing the technical loss by implementing various techniques [7] capacitor placement, reconductoring, voltage upgrade, reconfiguration, and integration with distributed generation sources.

11kV Padajungi Feeder of Gauradaha Distribution Centre is 136.4 km long and has maximum feeder load of 300 A [5]. The area fed are the various places of Eastern Nepal, the Gauradaha Municipality, Gaurigunj Rural Municipality and Kamal Rural Municipality of Jhapa District. These areas are largely agriculture based so for irrigation purpose the inductive motors are widely used. These inductive loads are a major factor causing the voltage levels to drop and hence household appliances are unable to operate due to poor voltage supply. Gauradaha DC has loss percentage of 11.88% in the Fiscal year 2078/79 [5].

Hence, this research focuses on performing a load flow analysis in 10 Bus Test system & 33 Bus Test system of Radial distribution configuration for the validation purpose with published literature and use the same methodology in a practical feeder (11kV Padajungi Feeder) in Nepal and implement the various techniques and their combination for loss reduction and efficiency improvement.

### **1.3 Research Objectives**

The main objective of this research is to improve the energy efficiency of a Power Distribution Network by Loss Reduction in a rural 11 kV Feeder of Nepal.

The specific objectives for meeting the main objective are:

- i. To perform load flow analysis on IEEE 10 Bus and 33 Bus Test System of Radial Distribution Configuration.
- ii. To perform load flow analysis on a practical 11 kV rural distribution feeder and determine its technical loss and efficiency.
- iii. To implement various reinforcement techniques for efficiency improvement such as:
  - Conductor upgradation
  - Capacitor placement
  - Integration with Solar PV
  - Conductor upgradation and Capacitor placement
  - Integration with Solar PV and Capacitor placement
- iv. Perform a financial analysis, analyze the results, and conclude.

### **1.4 Scope and Limitation**

Scope of the Study:

1. The study focuses on improving the energy efficiency of a specific Power Distribution Network, namely, a rural 11 kV Padajungi Feeder in Nepal.
2. The research includes the analysis of two test feeders (IEEE 10 Bus Test system and 33 Bus Test System) and a practical 11 kV rural distribution feeder.
3. Reinforcement techniques for efficiency improvement: conductor upgradation, capacitor placement, integration with Solar PV, and combinations of these techniques are only undertaken for study.
4. The study will also encompass financial analysis to assess the economic feasibility of the proposed efficiency improvement strategies.

### Limitations of the Study:

1. The research is limited to a single rural 11 kV feeder in Nepal, which may not represent the diversity of distribution networks in other regions or urban settings.
2. The analysis includes few specific reinforcement techniques, but there may be additional effective methods which are not considered in this study.
3. Capacitor placement locations on practical feeder is based on assumptions. For a more precise study, the locations should be identified by doing optimization calculations .

### **1.5 Report Organization**

This report is structured into five chapters. Chapter 1 includes an introductory overview of distribution system loss reduction techniques and concepts. Chapter 2 includes a concise literature review on energy efficiency and various methods for reducing losses. Chapter 3 outlines the research methodology and the tools and software utilized in this thesis. In Chapter 4, the results and discussions pertaining to the research are included. This chapter presents the various findings obtained during the research process. Chapter 5 concludes the report and provides recommendations for future research endeavors. References and Appendix are included at the report's conclusion.

## CHAPTER TWO : LITERATURE REVIEW

### 2.1 Literature Survey

Design and analysis of 11KV Distribution System using ETAP Software [2] centers on the development and enhancement of a distribution system within an urban electrical network. The primary objective of the study is to minimize power losses by employing feeder bifurcation and reconductoring methods. The system's efficiency is assessed through the utilization of Electrical Transient and Analysis Program (ETAP) software. The findings of the analysis reveal a 19.34% decrease in power losses with reconductoring and a 26.87% reduction with feeder bifurcation. Additionally, the results imply that using feeder bifurcation is a more cost-effective approach for mitigating higher losses.

Distribution Feeder Reconfiguration for Operation Cost Reduction [11] introduces a new algorithm for reconfiguring power distribution systems to reduce operating costs in real-time. This method, which relies on heuristics, gives precedence to cost reduction over a predefined time span as opposed to a single, static moment. The paper also takes into account practical factors related to feeder reconfiguration and how it aligns with other distribution automation tools. The algorithm has been transformed into production-ready software and has undergone testing on PG&E distribution systems, yielding favorable results. These test outcomes confirm the efficacy and robustness of the newly created algorithm.

Efficiency improvement on a distribution Feeder: A case Study is performed in [12]. The research paper revealed that a distribution feeder experienced a total loss of 38%, of which 22% constituted technical losses. The primary aim of the study was to diminish these technical losses by implementing conductor replacement, rerouting, and optimizing capacitor placement (OCP) strategies. The findings demonstrated that these interventions successfully reduced technical losses by 8%, elevating technical efficiency to 85.95%, in contrast to the previous efficiency level of 77.91%. Consequently, the overall system efficiency improved to 77.36%, accompanied by a non-technical loss of 10%. The paper underscores the significance of identifying the factors contributing to these losses and the imperative of their elimination to enhance the distribution system and meet consumer demands.

Optimal Capacitor Placement on Radial Distribution Systems [13] 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. The problem is presented as a mixed integer programming

problem and the solution methodology involves decomposing the problem into a master problem to determine the location of the capacitors and a slave problem to determine the type and size of the capacitors placed on the system. An efficient phase I - phase II algorithm is used to solve the slave problem and the proposed solution methodology has been tested and results are included in the paper.

Network Reconfiguration in Distribution Systems for Loss Reduction and Load Balancing is presented in [14]. This paper discusses the modification of the sectionalizing switches' status in the distribution system to achieve loss reduction and load balancing through network reconfiguration.

Optimal Capacitor Placement to Distribution Transformers for Power Loss Reduction in Radial Distribution Systems [15] proposes an approach to minimize power loss within a distribution system attributed to the Joule effect. The primary focus is on optimizing the placement of capacitor banks on the TRs to mitigate these losses. To address this challenge, the paper formulates the problem as a mixed-integer programming (MIP) model, aiming to maximize the net present value (NPV) of the capacitor installation project while adhering to various constraints. This MIP model is grounded in a specific formula for calculating power loss within a radial distribution system. Through experimentation within a segment of the Macau MV distribution system, the suggested approach has demonstrated its capability to significantly decrease power loss, enhance voltage levels, and yield a positive NPV for the utility.

Reconfiguration and Capacitor Placement for Loss Reduction of Distribution Systems by Ant Colony Search Algorithm is performed in [16]. The paper presents a novel swarm intelligence algorithm known as the Ant Colony Search Algorithm (ACSA) designed for enhancing the optimization of feeder reconfiguration and capacitor placement in distribution systems. Inspired by the behavior of ant colonies, this algorithm exhibits parallel search and optimization capabilities. The study's findings indicate that the ACSA approach outperforms both the Simulated Annealing (SA) and Genetic Algorithm (GA) methods in terms of reducing power loss, enhancing voltage profiles, and identifying optimal solutions. Moreover, ACSA is particularly well-suited for large-scale distribution systems, and the simultaneous consideration of feeder reconfiguration and capacitor placement proves to be a more effective strategy. These research outcomes have the potential to provide valuable insights for the automation and control management of distribution systems.

Load Factor Improvement of Distribution Feeders by Feeder Reconfiguration Using Modified BPSO Considering Losses is studied in [17]. The paper looks at how reconfiguring distribution feeders can lead to improved load factors. It also examines the cost of energy before and after the reconfiguration and found that there were both quantitative and qualitative benefits. Load aggregation, which takes advantage of diverse energy consumers, leads to an improvement in the load factor and attracts energy suppliers while giving consumers more bargaining power. The study found that while losses increased after reconfiguration, the cost of energy supply decreased, meeting all constraints. The results highlight the significance of load factor improvement in deregulated energy markets.

Minimizing Cost and Power loss by Optimal Placement of Capacitor using ETAP [9] examines the most advantageous positioning of capacitors in interconnected distribution systems featuring nonlinear loads through the utilization of ETAP. It conducts a comparative analysis among radial, loop, and interconnected systems and identifies the influence of harmonic components on optimal placement. The study's key takeaway is that capacitors can be effectively deployed for reactive power compensation, leading to improvements in power factor, reductions in system losses, and increased feeder capacity. Noteworthy outcomes include the determination of the optimal capacitor value and location, as well as enhancements in power factor and voltage. The paper emphasizes the importance of situating capacitors near inductive reactance kVAR loads and grouping them near load centers due to limitations in standard kVAR sizes.

Improving the Efficiency of Power Distribution Systems through Technical and Non-Technical Losses Reduction is studied in [7]. The paper concludes that improving the efficiency of distribution systems involves reducing both technical and non-technical losses. These losses can differ between developed and developing countries, but both can experience non-technical losses. 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. While results from research and simulations in these areas are encouraging, a successful strategy for improving distribution system efficiency requires a mix of both conventional and smart grid technologies.

Improvement of Power Delivery Efficiency of Distribution Systems Through Loss Reduction is presented in literature [18]. This paper presents a technique for mitigating losses within a single-source radial distribution system by reconfiguring the network and strategically placing

capacitors. In contrast to previous approaches, this novel method initially targets losses within the active component of branch currents and subsequently addresses losses associated with the reactive component. The approach is straightforward and relies solely on load flow solutions to reconfigure the network while determining the optimal capacitor size and placement. To evaluate its effectiveness, the method underwent testing on a 12.66 kV, 32-bus distribution system, yielding simulation results that indicated an annual energy savings of 1192.8 MWh and an enhanced voltage profile. These improvements were achieved by reducing system losses and alleviating the strain on substation equipment ratings.

Optimal Distributed Generation Placement in Power Distribution Networks: Models, Methods, and Future Research [19] offers an overview of the existing models and optimization approaches in the realm of Optimal Distributed Generation Placement (ODGP). The typical ODGP model entails the installation of multiple distributed generators (DGs) at different locations, with their size serving as the design variable, all with the aim of minimizing the overall power loss within the system. The methods employed to address the ODGP problem are categorized into three groups: analytical, numerical, and heuristic. Among these, the genetic algorithm and various heuristic algorithms are the most utilized techniques for tackling the ODGP problem. The paper also suggests that future research in this field is likely to concentrate on coordinated planning, dynamic ODGP, accounting for uncertainties and stochastic optimization, active network management, and islanded operation.

Load Flow Analysis of Radial Distribution System is studied in [20]. This paper conducts load-flow analysis by employing ETAP (version 14.0) software. This software simulates the present operational state of the steady-state system to assess parameters such as bus voltage profiles, active and reactive power flow, as well as losses.

Optimal Placement of Distributed Generation in Power System for Power System Loss Reduction Using ETAP [10] highlights the growing interest in renewable energy sources, which has spurred increased research into integrating Distributed Generation (DG) into power grids. One of the primary advantages of DG is its potential to reduce power losses and enhance the voltage profile. However, suboptimal placement of DG units can lead to increased power losses. Therefore, determining the most advantageous locations for DG units is crucial for optimizing overall system efficiency. To identify the optimal allocation of DG, optimization techniques are employed, and their impact on the power system is assessed in terms of reducing power losses. A study was conducted on a 10-bus system using ETAP software, demonstrating

that the installation of 5 MW of DG reduced active power losses from 3302.2 KW to 400.7 KW.

Optimal Reconfiguration of Radial Distribution Systems to maximize loadability [21] employs a 33-bus radial distribution system and devises a novel method for optimal reconfiguration. It presents an innovative approach to enhance the reconfiguration of radial distribution systems (RDS), which entails the selection of the most suitable branches for opening to achieve optimal system performance. A key objective in optimal reconfiguration is to maximize loadability. The paper introduces a fuzzy adaptation of the evolutionary programming algorithm to handle the discrete characteristics of the solution space. This algorithm aims to maximize a fuzzy index derived from a maximum loadability index to attain the optimal reconfiguration. The effectiveness of this approach is demonstrated through its application to a 33-bus RDS.

A Systematic Loss Analysis of Taipower Distribution System[22] presents a methodology for assessing power losses within Taipower distribution systems and the overall power network. This approach entails the development of artificial neural network (ANN) models designed to streamline the analysis of power loss in feeder lines, encompassing both overhead and underground configurations. The dataset used to train the ANN models was generated through load flow analyses aimed at quantifying power losses in test feeders across various scenarios. These ANN-based models were subsequently applied to calculate the power losses of all distribution feeders based on hourly power loading. The cumulative power loss for the entire Taipower system in 2003 was determined by aggregating the losses from both the distribution and transmission systems. The monthly power loss within the Taipower distribution system was calculated as 328,435 MWh, equivalent to 2.5% of total power generation or 3.6% of the total power supplied to all distribution feeders.

Calculation of T&D Loss Based on 11 0.4 KV Substation in a distribution utility is studied in [23]. This paper addresses the conventional method of calculating transmission and distribution (T&D) losses within a distribution utility, which typically relies on 11 KV feeders catering to diverse consumer types. Although the T&D loss percentage for a specific 11KV feeder might appear low, some of the 11/0.4 KV substations or distribution transformers associated with this feeder could exhibit elevated T&D losses. To pinpoint these high T&D losses, an extensive investigation was conducted, and this paper introduces a technique for identifying T&D losses within a specific consumer category using distribution transformer (DT) metering. Additionally, the paper presents a computational MATLAB program designed to directly compute T&D losses based on DT data.

Compensation and Enhancement of the Nigerian Power Systems Network is done in [24]. It performs a load flow analysis on the Kaduna 132/33 kV transmission station to assess its steady-state operational status. To achieve this, the researchers utilized the Electrical Transient Analyzer Program (ETAP) software, employing both the single line diagram and real data obtained from the station for modeling and analysis. To mitigate network losses, the Optimal Capacitor Placement (OCP) module within ETAP was applied. The findings revealed that several buses within the network experienced voltage deviations, and the overall system losses amounted to 753.2 kW and 10,437.3 kVAR. However, implementing OCP there was an enhancement in the voltage profiles of the affected buses, coupled with a reduction in losses to 586.1 kW and 8,015.7 kVAR. The OCP method strategically positioned and sized eight capacitor banks across eight candidate buses, resulting in the improvement of voltage profiles and a decrease in losses.

Improvement of Power Distribution System- A few Aspects is studied in literature [25] The paper 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.

Methods comparison for Optimal Capacitor Placement in Distribution System is studied in [26]. The paper explores diverse approaches to determine the ideal size and placement of capacitors within radial distribution systems. The overarching goals include mitigating power losses, enhancing voltage profiles and power factor, cost reduction, and maximizing economic benefits. These methods vary in terms of the information required, the outcomes they yield, their precision, efficiency, user-friendliness, and computational speed. The paper proceeds to compare outcomes achieved through ETAP and OpenDSS software using three distinct techniques: the genetic algorithm, the imperialist competitive algorithm, and the moth flame optimization. It suggests that the genetic algorithm stands out as the preferred method, particularly when employed alongside the ETAP program, due to its combination of speed and accuracy.

Power Distribution Problems on 11 kV Feeder Networks in Akure, Nigeria [27] 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 problems identified include low network availability due to load shedding and short circuit faults, and poor voltage profile due to substandard source-end voltage. The paper recommends routine maintenance practices, quick repair response, and standard input voltage from the Power Company to mitigate these problems.

Segregation of Technical and Commercial Losses in an 11 kV Feeder is performed in [28]. The study aimed to distinguish between technical and commercial losses and found that commercial losses were significantly higher than technical losses. It was found that all the transformers in the feeder were adequately loaded. Empirical formulas were used to calculate technical losses, and the difference between the manual and software-calculated technical losses was only about 5%, likely due to differences in estimation methods. Therefore, empirical formulas may be suitable for calculating losses for smaller feeders. While using software can help identify major loss sections, overload or underload on transformers, and other useful aspects for reliable feeder operation.

The impact of distributed generation on transmission and distribution losses in Sri Lanka power system is studied in [29]. This paper concentrates on evaluating the economic consequences of distributed generation on the transmission and distribution network within Sri Lanka. The research encompasses network simulation studies conducted on the transmission network and four grid substations, all interconnected with multiple DGs. The findings indicate a decline in transmission network losses as DG penetration increases. However, the magnitude of distribution network losses is contingent on the quantity of DG capacity integrated. Nonetheless, the overall network losses are diminished, resulting in financial advantages stemming from the inclusion of DGs within the system.

Power Loss Reduction of 11kV Feeder using Capacitor Banks to Distribution Transformers- A Case Study [8] A load flow analysis was executed to evaluate various aspects, including feeder losses, the load on 11 kV lines, distribution transformers, and voltage levels at different feeder points. The proposed model integrates the installation of capacitors to fulfill the reactive power needs of the existing system. The paper conducts a comparative analysis between the system with and without capacitor banks.

Optimal D-STATCOM Placement in Radial Distribution System Based on Power Loss Index Approach is presented in [30]. The paper outlines the application of the power loss index

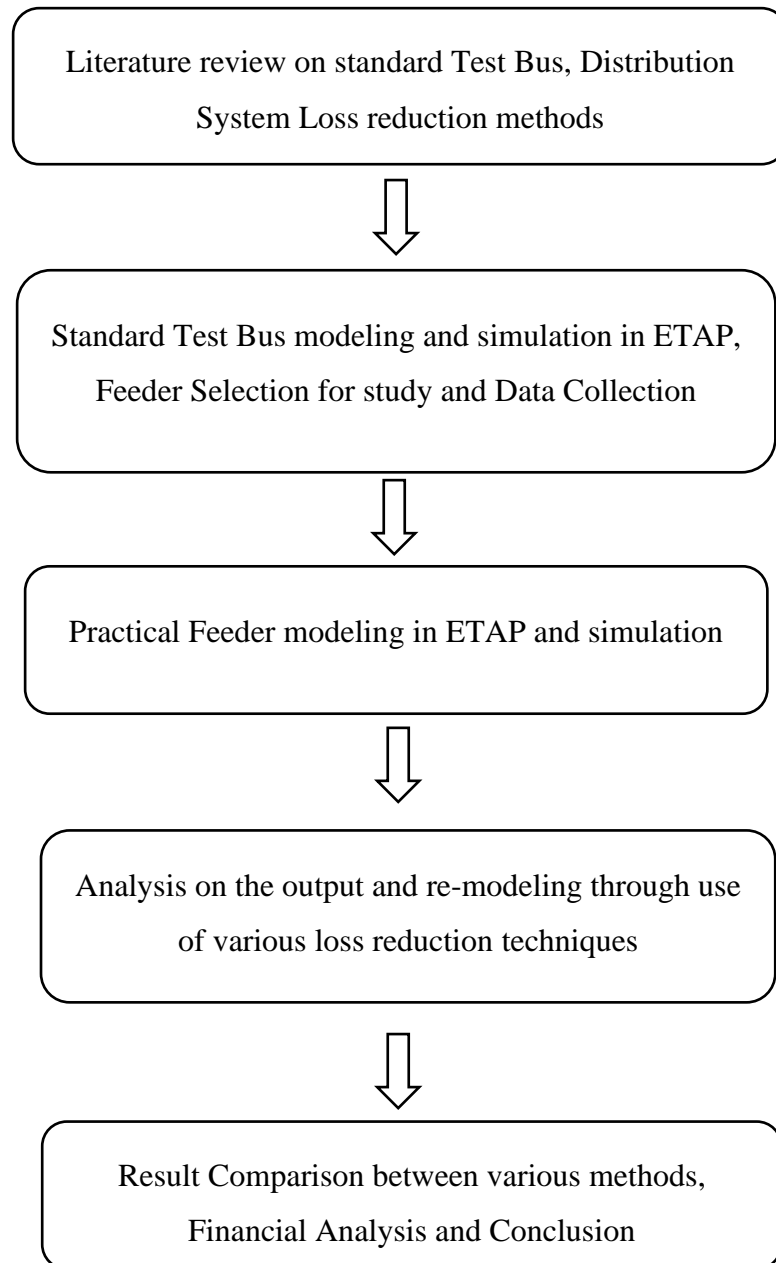
technique for identifying the optimal placement of a D-STATCOM (Distribution Static Synchronous Compensator) within a radial distribution system. The primary objectives are to minimize line losses and enhance voltage profiles. The process involves computing the load flow to ascertain the bus characteristics and employing mathematical modeling for D-STATCOM to calculate reactive power injections at all bus locations. Subsequently, the power loss index method is deployed to identify the most suitable location for the D-STATCOM based on the reactive power magnitude. This algorithm undergoes testing using MATLAB software on radial distribution systems with 10, 33, and 69 buses, following which the results reveal a reduction in line losses and an improvement in voltage profiles across all test systems.

## **2.2 Research Gap**

Through the literature reviews it is concluded that Feeder reconfiguration, integration with distributed generation, optimal capacitor placement, shift toward smart grid, conductor upgradation, feeder bifurcation etc. are the widely used techniques in distribution system planning and loss reduction of the system. It can also be seen that only a few research have implemented the combination of these strategies. Therefore, it is intended to perform a distribution system analysis in ETAP simulation software through load flow analysis and implement the various reinforcement techniques and their combination for loss reduction, perform a financial analysis for the associated cost on the loss reduction and ultimately increase the energy efficiency of a practical distribution feeder in Nepal's power system.

## CHAPTER THREE : METHODOLOGY

### 3.1 Study Design and Methodology



**Figure 3.1 Research Methodology**

Figure 3.1 presents a simple flow diagram for the research methodology implemented while doing this research. The study is first performed in Test Feeder. Test Feeder is an electric power distribution system model that has been made public by the IEEE PES Distribution System Analysis Subcommittee. Most of the test feeders are based on simplifications of actual feeders. Researchers are encouraged by IEEE to incorporate findings from at least one test feeder [31].

IEEE believes this approach serves multiple purposes: it enables authors to distinctly highlight their contributions, lessens the requirement to publish system data [31].

This study incorporates three radial configuration feeders: the IEEE 10 Bus, the 33 Bus Test Feeder, and a practical 11 kV feeder. The test system is replicated within ETAP software, where a load flow analysis is conducted. This identical methodology is applied to the practical feeder. To select a distribution feeder from Nepal's power system, a combination of primary and secondary data is employed. The feeder is then modeled using Google Earth, utilizing the distribution transformer locations and conductor types. For the existing conditions of the feeder, ETAP is used for modeling, and load flow analysis is executed to determine voltage levels at various buses and assess power losses. The same system undergoes remodeling with the implementation of various loss reduction techniques. The study subsequently analyzes and compares the results against the initial data. Finally, a financial analysis is conducted to determine the most effective solution for loss reduction.

### 3.2 Research instrument

The study is carried out using the "ETAP-Electrical Transient and Analysis Program," an electrical network modeling and simulation software. This tool is commonly employed by power system engineers for constructing a digital twin of electrical systems and evaluating the dynamics, transients, and protection of electrical power systems.

### 3.3 Problem Formulation

#### 3.3.1 Power Loss and Current Formulation

The current in branch (i,k) connecting buses i and k is given by[32] [33]

$$I_{ik} = \frac{P_{ik} - jQ_{ik}}{V_i} \quad (1)$$

Where,

$I_{ik}$  = Current through branch (i,k)

$P_{ik}$  = Total real power flow in the branch (i,k)

$Q_{ik}$  = Total reactive power flow in the branch (i,k)

$V_i$  = Voltage at node i

And the total Power loss in the line is [33]

$$TPL = \sum_{ik=1}^n |I_{ik}|^2 R_{ik} \quad (2)$$

Where,

$I_{ik}$ = Current through branch (i,k)

$R_{ik}$ = Resistance of branch (i,k)

A branch current can be divided into two parts: active component ( $I^a$ ) and reactive component ( $I^r$ ). The overall loss linked to both the active and reactive components of a branch current can be expressed as follows [33] :

$$TPL = TPL_a + TPL_r \quad (3)$$

Therefore,

$$TPL = \sum_{ik=1}^n |I_{ik}^a|^2 R_{ik} + \sum_{ik=1}^n |I_{ik}^r|^2 R_{ik} \quad (4)$$

The capacitor draws a reactive current  $I_c$  and for a radial grid it changes only the reactive component of current of branch set  $\alpha$ . The current of other branches is unaffected by the capacitor. The new reactive current of the (i,k)<sup>th</sup> branch is given by :

$$I_{rik}^{new} = I_{ik}^r + D_{ik} I_c \quad (5)$$

Where,

$D_{ik} = 1$  , if branch (i,k)  $\in \alpha$

$D_{ik} = 0$  , otherwise

From equation (4) and (5) the total loss saving (TLS) can be expressed as :

$$TLS = \sum_{ik=1}^n (2D_{ik} I_{ik}^r + D_{ik} I_c^2) R_{ik} \quad (6)$$

The capacitor current  $I_c$  that provides the maximum loss saving can be obtained from  $dS/dI_c = 0$  then

$$\sum_{ik=1}^n (2D_{ik} I_{ik}^r + D_{ik} I_c^2) R_{ik} = 0 \quad (7)$$

Thus, the capacitor current for maximum loss saving is given by [32], [33]

$$I_c = \frac{-\sum_{ik \in \alpha} I_{ik}^r R_{ik}}{\sum_{ik \in \alpha} R_{ik}} \quad (8)$$

### 3.3.2 Capacitor Placement

The cost associated can be expressed in mathematical terms as [33]:

$$\text{Min Objective Function} = \sum_{i=1}^N \text{Bus} (x_i C_{0i} + Q_{ci} C_{1i} + B_i C_{2i} T + C_2 \sum_{i=1}^{\text{Nload}} (T_i P_L^i)) \quad (9)$$

Where,

$N$  = Number of bus candidate

$x_i = 0/1$ , 0 means no capacitor installed at bus  $i$

$C_{0i}$  = Installation cost

$C_{1i}$  = Cost of installation capacitor bank per kVAR

$Q_{ci}$  = Capacitor Bank size (kVAR)

$B_i$ = Capacitor Bank (No. of)

$C_{2i}$ = Operating cost of per bank per year

$T$  = Planning period (years)

$C_2$ = Cost of each kWh loss in Rs/kWh

$L$  =Load levels (maximum, average and minimum)

$T_i$ = Time duration, in hours, of load level

$P_L^l$ = Total System loss at load level 1 constraints

### 3.3.3 Conductor Sizing

The objective function that needs to be minimized considers both the cost of the conductor and the present value of losses associated with power and energy losses occurring over the lifespan of the feeder [34].

$$\text{Min } Z = \sum_{i \in n} K_{Ti} = \sum_{i \in n} (K_{1i} + K_{2i}) \quad (10)$$

$$K_{1i} = ccL_iA_i \quad (11)$$

$$K_{2i} = K_{1i}/A_i \quad (12)$$

$$K_{1i} = 26.28\rho L_i K_{gro} I_i^2 \quad (13)$$

$$K_{gro} = \sum_{p=1}^m \frac{(1+g)^{2p}(Cp'_p + Ce_p llf_p)}{(1+dr)^p} + (1+g)^{2m}(llf_m) * \sum_{p=m+1}^F (Cp'_p + Ce_p llf_p) / (1+dr)^p$$

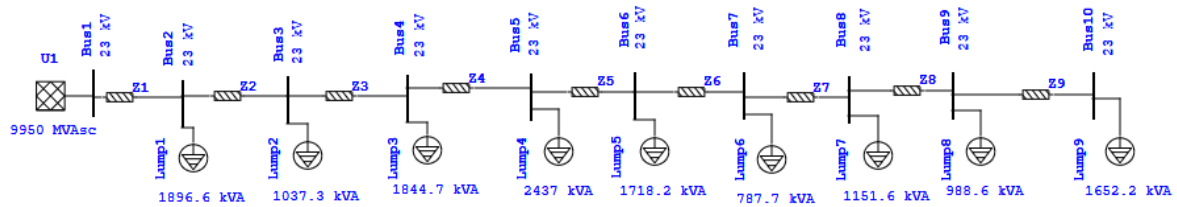
$$Cp'_p = Cp_p / 8760 \quad (14)$$

where  $K_{Ti}$  represents the total cost of the feeder which is comprised of two components: the cost of the conductor  $K_{1i}$  and the cost of losses  $K_{2i}$ . These costs are directly proportional to the cross-sectional area  $A_i$  ( $mm^2$ ). The variables involved include 'n,' which denotes the total number of feeder segments;  $L_i$  representing the length of the i-th feeder segment in kilometers;  $I_i$  representing the diversified current in that same segment measured in Amperes; 'cc' as a constant associated with the variable installation cost of the feeder in Rs. per  $mm^2$  /km;  $\rho$  representing the resistivity of the conductor material in ohm- $mm^2$  /km;  $K_{gro}$  is a constant associated with the present worth of the cost of energy and power losses throughout the lifespan of the feeder, accounting for factors such as increased load, load factor, and energy and power cost;  $Cp_p$  and  $Ce_p$  denote the cost of power and energy in the 'p'-th year, respectively;  $llf_p$  represents the load loss factor in the 'p'-th year;  $dr$  stands for the annual discount rate; 'g' is the annual load growth rate, 'm' signifies the considered load growth period for the feeder, and 'F' represents the lifespan of the feeder in years [34].

## CHAPTER FOUR : RESULTS AND DISCUSSION

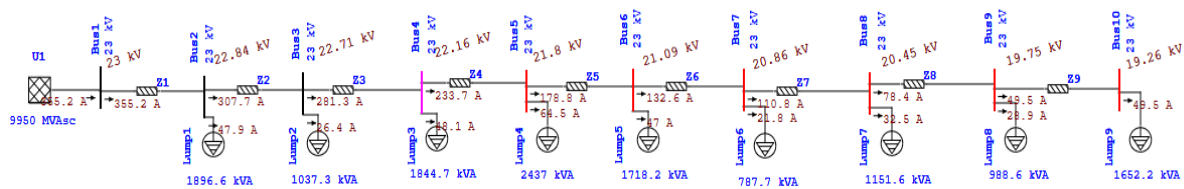
### 4.1 Modelling of IEEE 10 Bus System

The load and line information for the IEEE 10 Bus test system is sourced from [35].



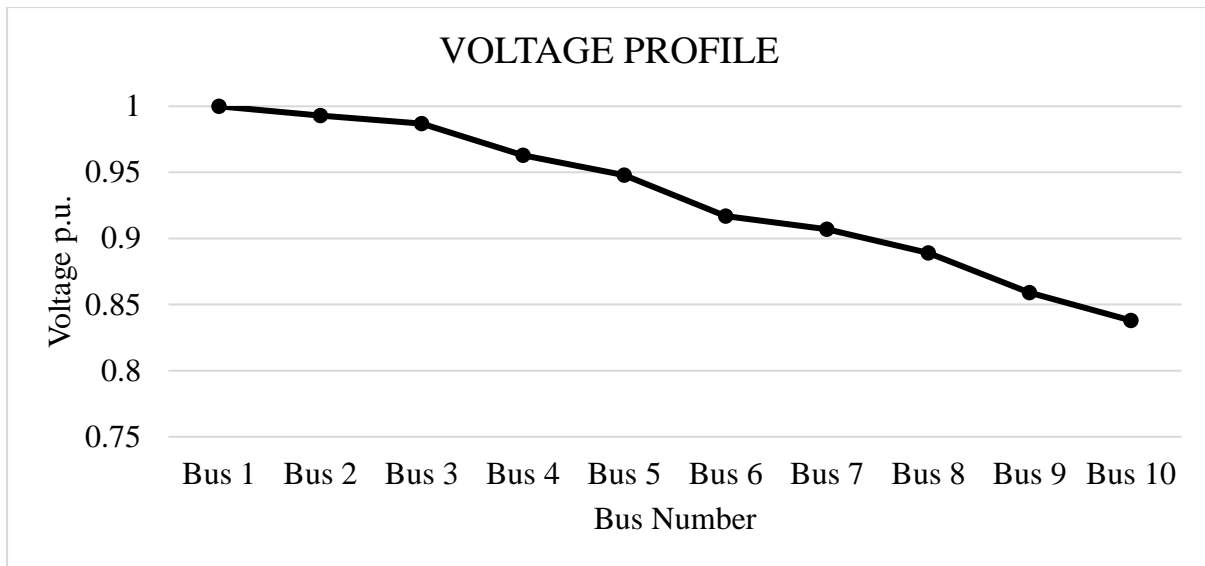
**Figure 4.1 IEEE 10 Bus Radial Distribution System**

Figure 4.1 shows the Line Diagram of IEEE 10 Bus Radial Distribution system as modelled in ETAP. The system data is mentioned in Appendix -A



**Figure 4.2 Load Flow Result of IEEE 10 Bus System**

Figure 4.2 shows the result of load flow of IEEE 10 Bus System. The Base voltage of the system is 23kV. The voltage at the bus diminishes as it moves from the grid towards the feeder, starting at the sending end and progressing to the receiving end, as depicted in Figure 4.3's voltage profile. Voltage drop by 3.74 kV is observed at the receiving end and loss percentage is 5.96%



**Figure 4.3 Voltage Profile of IEEE 10 Bus System**

Figure 4.3 shows the voltage profile of the system. Table 4.1 shows the load flow result of IEEE 10 Bus System. The total active load is 13.15 MW and active loss is 0.784 MW resulting in a 5.96 % loss. The obtained loss is equal to the loss obtained in [30], [35]– [37] . The research study [37] has identified Bus 5,6,9,10 as candidate bus whereas [38] has identified Bus 2,3,4,5 and 6 as candidate bus for optimal location both studies being based on Loss Sensitivity Index and Particle Swarm Optimization. Thus, the same bus as in [38] are selected as candidate bus and total of 6000 kVAR capacitor is installed and load flow study is carried out in this study and the result obtained are tabulated in Table 4.1.

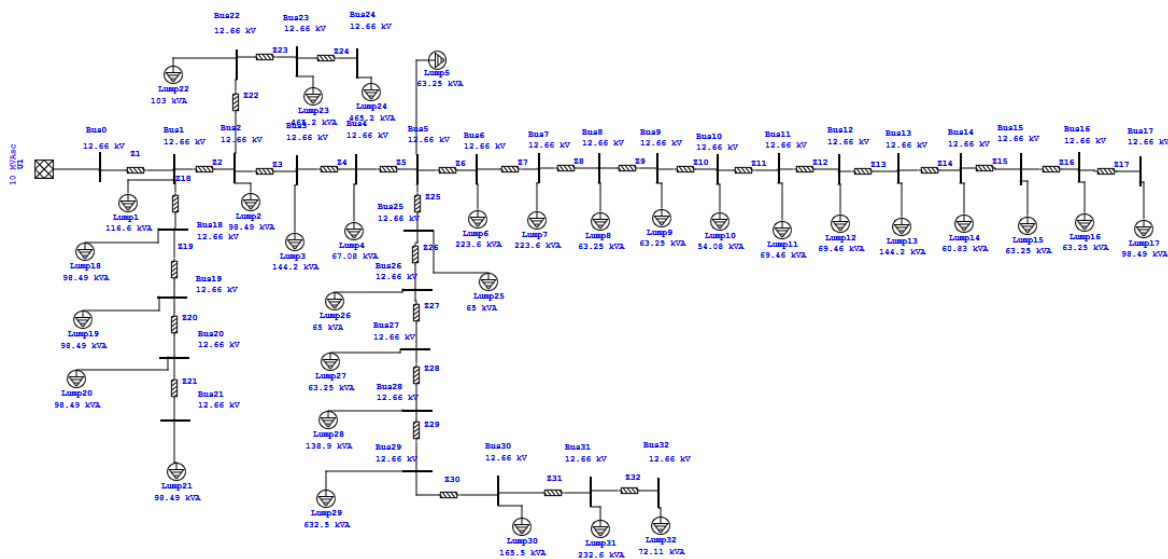
**Table 4.1 Load Flow Result of IEEE 10 Bus System**

Study ID	IEEE 10 Bus Base Case	IEEE 10 Bus After OCP
Configuration	Radial	Radial
Buses	10	10
Branches	9	9
Power Grids	1	1
Loads	9	9
Load-MW	13.152	13.063
Load-Mvar	5.223	-0.656
Generation-MW	13.152	13.063
Generation-Mvar	5.223	-0.656
Loss-MW	0.784	0.695
Loss-Mvar	1.037	0.897
Loss-MW%	5.96 %	5.32 %

After the capacitor placement the loss is reduced from 5.96% to 5.32% i.e., the active power loss drops from 0.784 MW to 0.695 MW. Following the incorporation of a D-STATCOM with a capacity of 9608.5 kVar into the IEEE 10 Bus Test System, as per the Power Loss Index approach described in study [30] the active power loss has been decreased from 0.783 MW to 0.738 MW. However, using capacitor the loss of 0.695 MW is achieved in this study. Also, the study [37] has shown loss drop from 0.784 MW to 0.696 MW. Here the drop is equal, but it has installed 3186 kVAR capacitor. So, it has achieved the same level of loss with less capacity of capacitor being installed than this study.

#### 4.2 Modelling of IEEE 33 Bus System

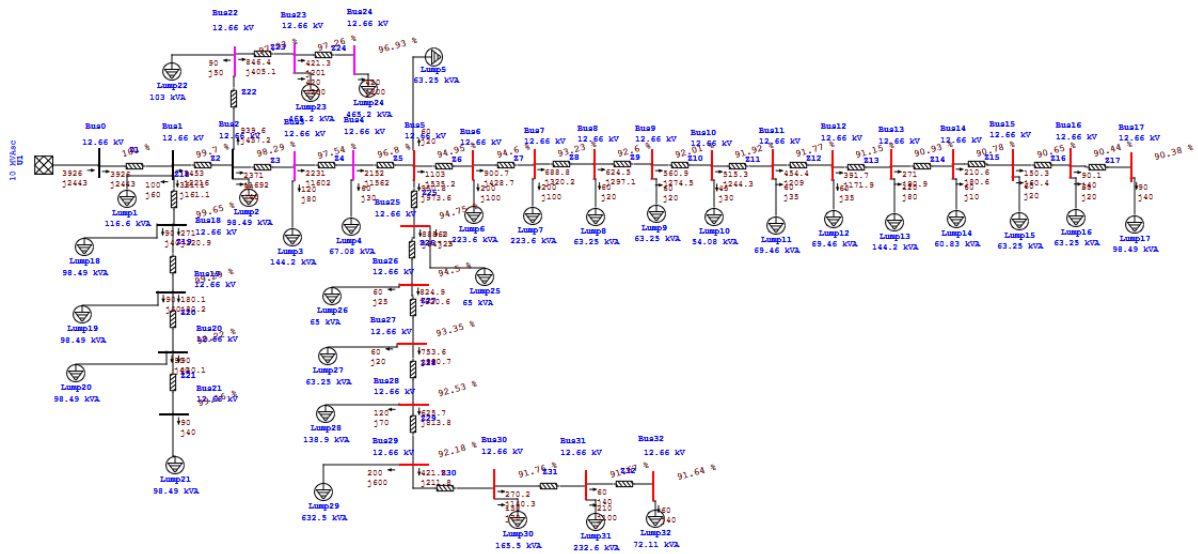
The data for the IEEE 33 Bus test system is obtained from [21]. Figure 4.4 displays the Single Line Diagram of the IEEE 33 Bus Radial Distribution system, as it has been represented in the ETAP. The system data is mentioned in Appendix -B



**Figure 4.4 IEEE 33 Bus Radial Distribution System**

The IEEE 33 Bus Radial Distribution System operates at a base voltage of 12.66 kV and comprises a network of 33 interconnected buses with diverse load conditions. A Load Flow

analysis is conducted, and the results are depicted in Figure 4.5, which corresponds to the modeled configuration shown in Figure 4.6.

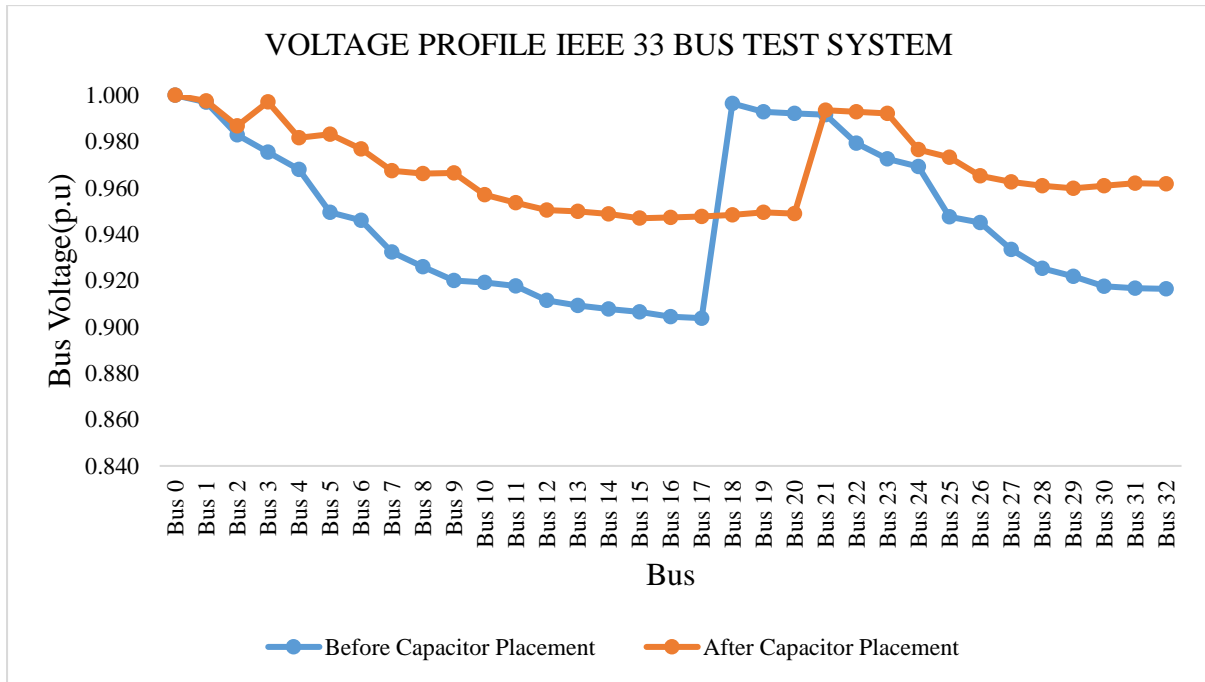


**Figure 4.5 Load Flow Result of IEEE 33 Bus System**

Figure 4.5 shows the result of load flow of IEEE 33 Bus System. The Base voltage of the system is 12.66 kV. It is found that the bus voltages decrease from the grid towards the feeder from the Sending end to the receiving end. Considering voltage deviation of 7%, the Bus nodes with voltage less than 93% are considered as the candidate node for optimal capacitor placement and the capacitors are installed as shown in Table 4.2

**Table 4.2 Capacitor Bank for IEEE 33 Bus System**

S.N	Candidate Bus	Capacitor Size (kVAR)
1.	Bus 9	300
2.	Bus 15	300
3.	Bus 16	300
4.	Bus 29	600
5.	Bus 31	900
Total		2400



**Figure 4.6 Bus Voltage Comparison of IEEE 33 Bus System Before and After CP**

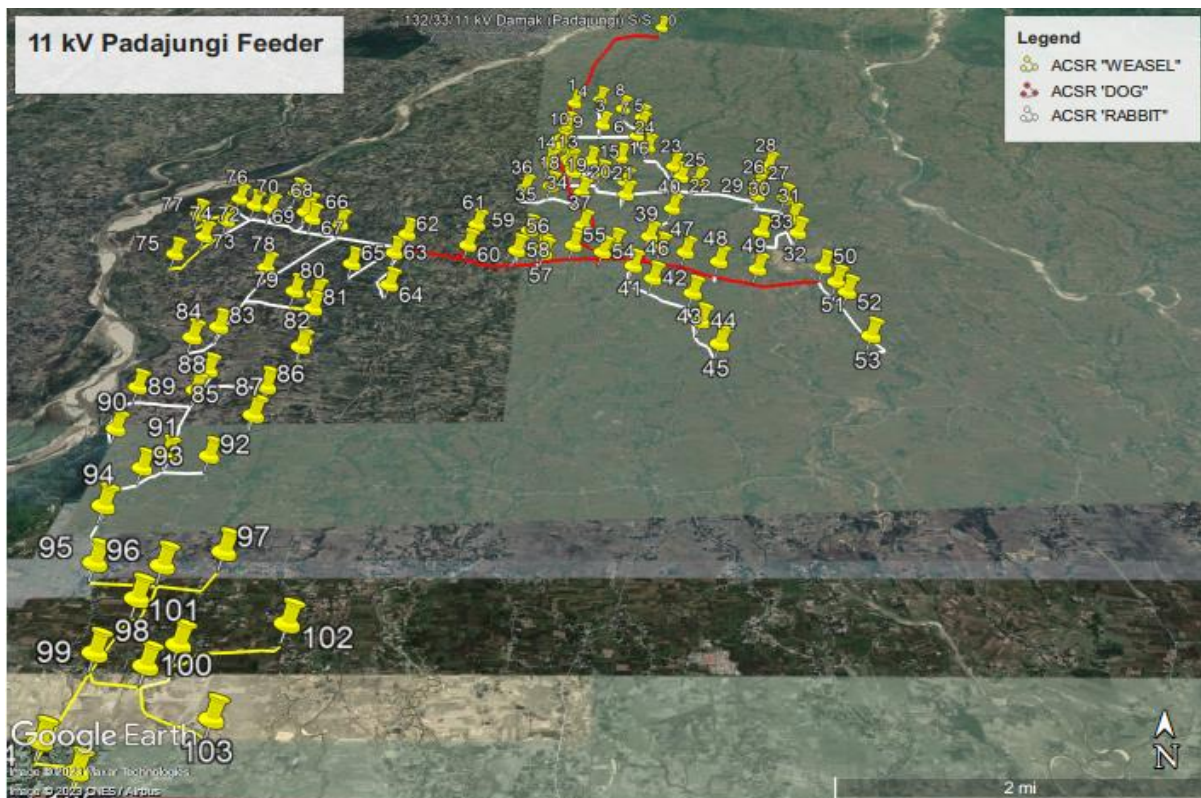
Figure 4.6 shows the Bus voltage in percentage Before and after the capacitor placement. The lowest voltage value is 0.904 p.u. before the capacitor placement. The capacitor bank of total size of 2400 kVAR is connected at various bus which boosts the voltage keeping the minimum bus voltage 0.947 p.u.

**Table 4.3 Load Flow Result of IEEE 33 Bus System**

Study ID	IEEE 33 Bus Base Case	IEEE 33 Bus After CP
Configuration	Radial	Radial
Buses	33	33
Branches	32	32
Power Grids	1	1
Loads	32	32
Load-MW	3.926	3.869
Load-Mvar	2.443	0.48
Generation-MW	3.926	3.869
Generation-Mvar	2.443	0.48
Loss-MW	0.211	0.154
Loss-Mvar	0.143	0.107
Loss-MW%	5.37%	3.98%

Table 4.3 shows the load flow result of the 33 Bus System. The active loss obtained in the study is 0.211 MW which is same as that of [21] [30]. In this study the loss has reduced from 5.37% to 3.98% i.e., from 0.211 MW to 0.154 MW whereas in [30] the loss is reduced to 0.157 MW.

### 4.3 Modelling of Practical 11 kV Feeder



**Figure 4.7 11 kV Padajungi Feeder Mapped in Google Earth**

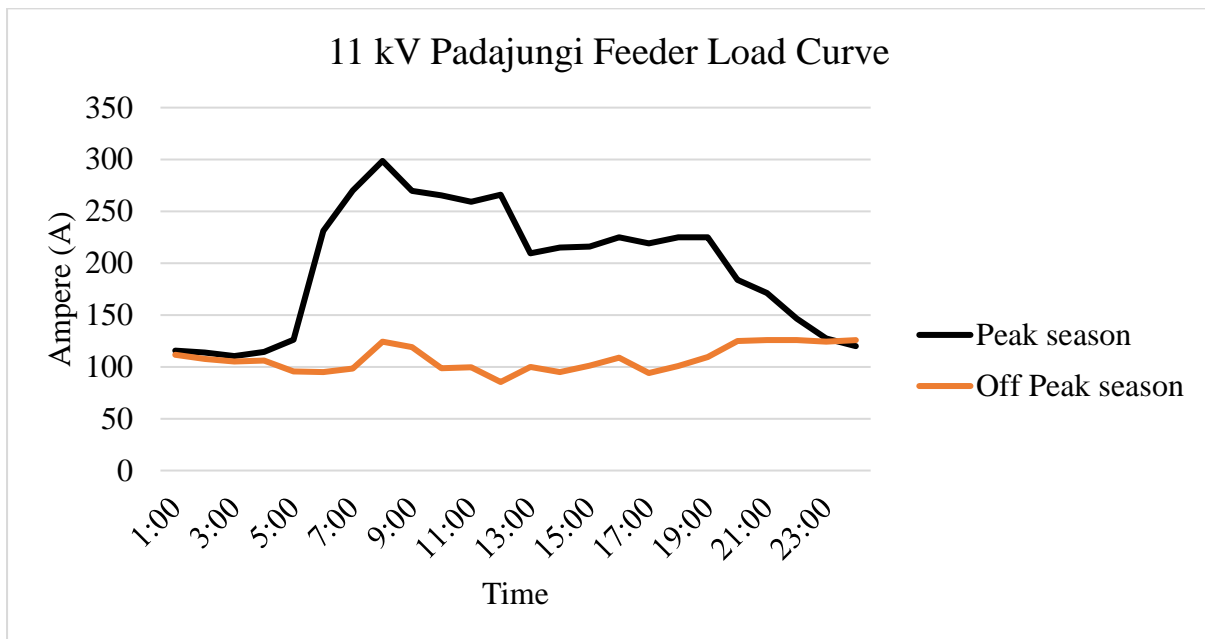
Figure 4.7 shows the location of various distribution transformers along the 11 kV Padajungi feeder route being mapped in Google Earth. 11 kV Padajungi Feeder originates from the 132/33/11 kV Damak (Padajungi) Substation. It is 136.4 km long and has maximum feeder load of 300 A [5]. The area fed are the various places of Eastern Nepal, the Gauradaha Municipality, Gaurigunj Rural Municipality and Kamal Rural Municipality of Jhapa District. These areas are largely agriculture based so for irrigation purpose the inductive motors are widely used. These inductive loads are a major factor causing the voltage levels to drop and hence household appliances are unable to operate due to poor voltage supply. Gauradaha DC has loss percentage of 11.88% in the Fiscal year 2078/79 [5].

The Single line diagram of the feeder is obtained from NEA Gauradaha Distribution Center and is attached in Appendix E. The bus and branch data of the feeder is calculated and is mentioned in Appendix C.

Appendix F shows the 11 kV Padajungi Feeder ETAP Model. The ETAP model contains 92 Distribution Transformers of 50, 100, 200 and 300 kVA ratings. The loss report generated by ETAP shows loss of 12.18% and efficiency of 87.82%.

### 4.3.1 Load Curve of 11 kV Padajungi Feeder

Figure 4.8 shows the Load curve of 11 kV Padajungi Feeder at peak season (2079/12/26) and off peak season (2079/04/06). The load data was collected from the daily log sheet of 132/33/11 kV Damak (Padajungi) Substaion. The load curve shows daily peak of 299 A and minimum of 110 A at the peak season where the agricultural loads are operated. Similarly, during the off season daily peak of 126 A and minimum of 85 A is observed.



**Figure 4.8 Load Curve of 11 kV Padajungi Feeder**

Table 4.4 shows the loading data of 11 kV Padajungi feeder. The hourly load factor are evaluated and averaged to obtain the daily load factor.

**Table 4.4 11 kV Padajungi Feeder load**

Time	Ampere loading on 2079/12/26	Load Factor	Ampere loading on 2079/04/06	Load Factor
1:00	116	0.39	112	0.89
2:00	114	0.38	108	0.85
3:00	110	0.37	105	0.84
4:00	114	0.38	106	0.84
5:00	126	0.42	96	0.76
6:00	231	0.77	95	0.75
7:00	270	0.90	98	0.78
8:00	299	1.00	124	0.99
9:00	270	0.90	119	0.95
10:00	265	0.89	99	0.79
11:00	259	0.87	100	0.79

Time	Ampere loading on 2079/12/26	Load Factor	Ampere loading on 2079/04/06	Load Factor
12:00	266	0.89	85	0.68
13:00	210	0.70	100	0.79
14:00	215	0.72	95	0.76
15:00	216	0.72	101	0.80
16:00	225	0.75	109	0.87
17:00	219	0.73	94	0.75
18:00	225	0.75	101	0.80
19:00	225	0.75	110	0.87
20:00	184	0.62	125	0.99
21:00	171	0.57	126	1.00
22:00	147	0.49	126	1.00
23:00	128	0.43	124	0.99
0:00	120	0.40	126	1.00
Max	299		126	
Average		0.66		0.86

The average load factor of the feeder is obtained as 0.66 in the peak season whereas 0.86 in the off peak season.

#### 4.3.2 Technical Loss Reduction Techniques

##### I. Conductor upgradation (CU)

Table 4.5 shows the details of existing conductor in the feeder and the total length upgraded to a higher cross section and rating conductor. 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.

**Table 4.5 Conductor Upgradation of 11kV Padajungi Feeder**

Existing (Base)	Upgraded to	Length (km)
ACSR WEASEL	ACSR RABBIT	12.43
ACSR RABBIT	ACSR DOG	48.34
Total		60.77

##### II. Capacitor Placement

Five capacitor banks are positioned at different bus locations. A cumulative capacity of 5 MVAR in capacitor banks is distributed across these five locations, providing reactive power support to the system. This information is presented in Table 4.6, outlining the reactive power contributions from the capacitor banks.

**Table 4.6 Capacitor Placement in 11 kV Padajungi Feeder**

Candidate Bus No.	Capacitor (kVAR)
Bus 66	1000
Bus 91	1000
Bus 37	1000
Bus 22	1000
Bus 49	1000
<b>Total</b>	<b>5000</b>

### III. Solar PV Integration

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 Table 4.7 [39]. 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 and Irradiance level is calculated from the ETAP to be 918  $W/m^2$

**Table 4.7 Solar PV System Technical Specification [39]**

Manufacturer	Suniva
Type	Mono-Crystalline
Cells	60
Model	ART245-60-3-1
Nominal Power	239.7 W
Voltage at Nominal Power	30.65 V
Current at Nominal Power	7.82 A
Open-circuit Voltage	37.08 V
Short-circuit Current	8.33 A
Voltage Temperature Coefficient	-0.332 % / C
Current Temperature Coefficient	0.036 % / C
Module Efficiency	14.9 %
Length	165.3 cm
Width	98.2 cm
Area	1.62 $cm^2$

### IV. Conductor Upgradation and Capacitor Placement

A combined method including the conductor upgradation as mentioned in Method I and Capacitor Placement as mentioned in Method II is studied.

## V. Solar PV Integration and Capacitor Placement

A combined method including the Solar PV Integration as mentioned in Method III and Capacitor Placement as mentioned in Method II is studied.

### 4.3.3 Load Flow Study

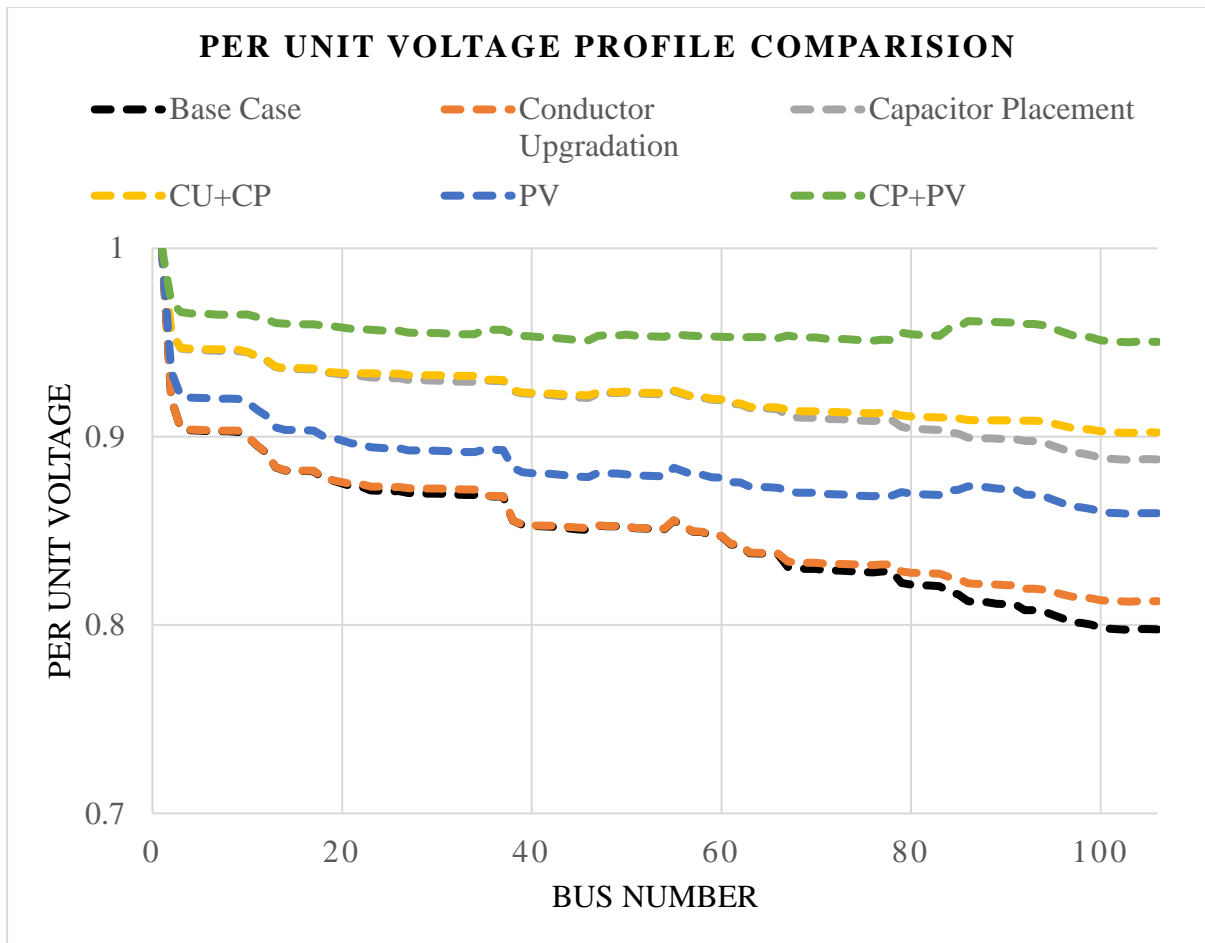
#### A) Loading at 50%

Considering these options, load flow study is carried out and the report generated is tabulated in Table 4.8, the per unit voltage profile comparison is presented in Figure 4.9, Loss Comparison is presented in Figure 4.10 and Efficiency improvement while implementing various techniques is shown in Figure 4.11

The model contains 104 loads from 104 Distribution Transformers of 50, 100, 200 and 300 kVA ratings. The report generated by ETAP shows loss of 12.18% and efficiency of 87.82%.

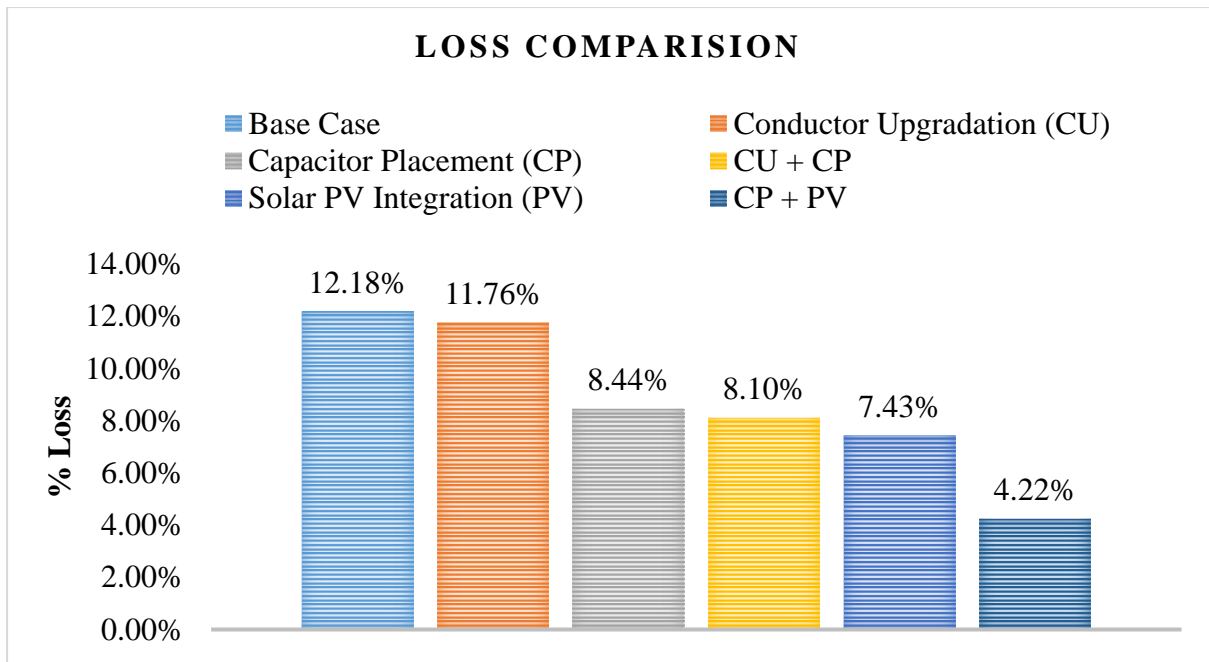
**Table 4.8 Load Flow Summary**

ID	Base Case	Conductor Upgradation	Capacitor Placement	Conductor Upgradation and Capacitor placement	Solar PV Integration	Solar PV integration and Capacitor placement
Buses	106	106	106	106	106	106
Branches	105	105	105	105	105	105
Generators	0	0	0	0	0	0
Power Grid	1	1	1	1	1	1
Loads	104	104	104	104	104	104
Load-MW	3.359	3.351	3.399	3.395	3.27	3.341
Load-Mvar	2.329	2.33	0.173	0.16	2.173	-0.129
Generation-MW	3.359	3.351	3.399	3.395	3.27	3.341
Generation-Mvar	2.329	2.33	0.173	0.16	2.173	-0.129
Loss-MW	0.409	0.394	0.287	0.275	0.243	0.141
Loss-Mvar	0.501	0.498	0.349	0.348	0.298	0.171
Loss %	12.18%	11.76%	8.44%	8.10%	7.43%	4.22%



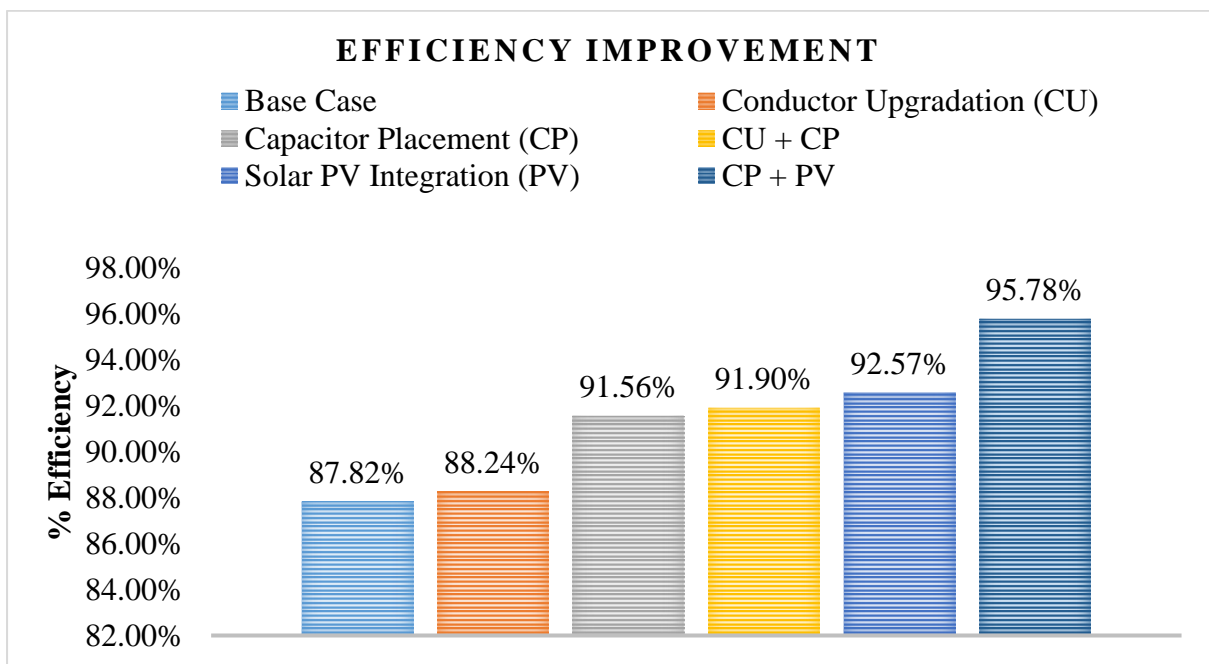
**Figure 4.9 Per Unit Voltage Profile Comparison**

Figure 4.9 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. The complete summary of percentage voltage report generated is presented in Appendix D



**Figure 4.10 Loss Comparison**

Figure 4.10 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 4.11 Efficiency Improvement**

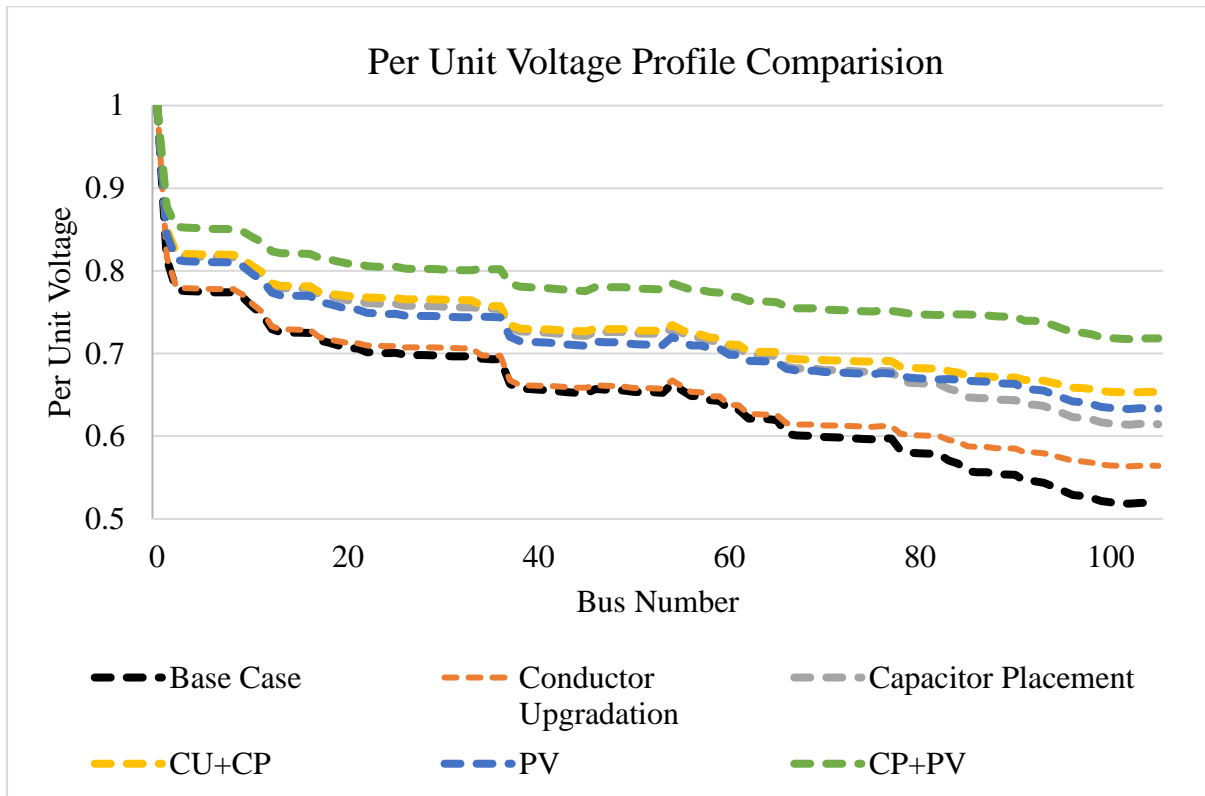
Figure 4.11 shows the efficiency of the distribution network. It can be observed that through the introduction of various reinforcement techniques the efficiency of the power distribution network can be increased.

B) Loading at 80%

The model of 11 kV Padajungi Feeder has been simulated by increasing the loading to 80% and technical loss has been evaluated.

**Table 4.9 Load Flow Summary**

ID	Base Case	Conductor Upgradation	Capacitor Placement	Conductor Upgradation and Capacitor placement	Solar PV Integration	Solar PV integration and Capacitor placement
Buses	106	106	106	106	106	106
Branches	105	105	105	105	105	105
Generators	0	0	0	0	0	0
Power Grid	1	1	1	1	1	1
Loads	104	104	104	104	104	104
Load-MW	7.311	7.2	6.96	6.901	6.76	6.58
Load-Mvar	5.843	5.777	4.011	3.946	5.054	3.182
Generation-MW	7.311	7.2	6.96	6.901	6.76	6.58
Generation-Mvar	5.843	5.777	4.011	3.946	5.054	3.182
Loss-MW	2.196	2.047	1.596	1.501	1.414	0.977
Loss-Mvar	2.673	2.584	1.945	1.894	1.741	1.206
Loss %	30.04%	28.43%	22.93%	21.75%	20.92%	14.85%



**Figure 4.12 Per Unit Voltage Profile Comparison**

Figure 4.12 shows the per unit voltage at various buses at 80% loading of Distribution Transformers. The minimum p.u. voltage at Base case is 0.51. After conductor upgradation there is a negligible change in the minimum p.u. voltage and is 0.56. After capacitor placement it rises to 0.61 p.u. Similarly, after combination of conductor upgradation and capacitor placement is introduced the minimum p.u. voltage is 0.65, and as Solar PV is integrated alone the minimum voltage is 0.633 p.u. and after capacitor placement and solar PV integration the minimum voltage is 0.718 p.u. Thus, by employing different approaches, the minimum voltage can be elevated; however, as the load factor of the feeder rises, reducing losses becomes challenging. With an increase in loading, the current passing through the conductor also rises, leading to a proportional increase in technical losses. Consequently, in cases of heightened loading, segregating the feeder is preferable to applying reinforcement techniques. As the loading intensifies, the bus end voltage experiences dips, creating challenges in enhancing the voltage profile within the feeder. Therefore, beyond a certain point of increased loading, the substantial improvement of voltage dipping in the feeder through the implementation of reinforcement techniques becomes impractical.

### 4.3.4 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) [40]

Solar PV / kW: Rs. 73637.06 [41]

Revenue per kWh: Rs. 9.72 [5]

#### B) Energy Loss Calculation

The energy loss of the network can be estimated from the Loss Load Factor (LLF) method using the following relations [29]:

$$\text{Energy Loss} = \text{Power Loss} * \text{Time} * \text{LLF}$$

And, 
$$\text{LLF} = a * (\text{Load Factor}) + b * (\text{Load Factor})^2$$

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 4.8

Figure 4.13 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.

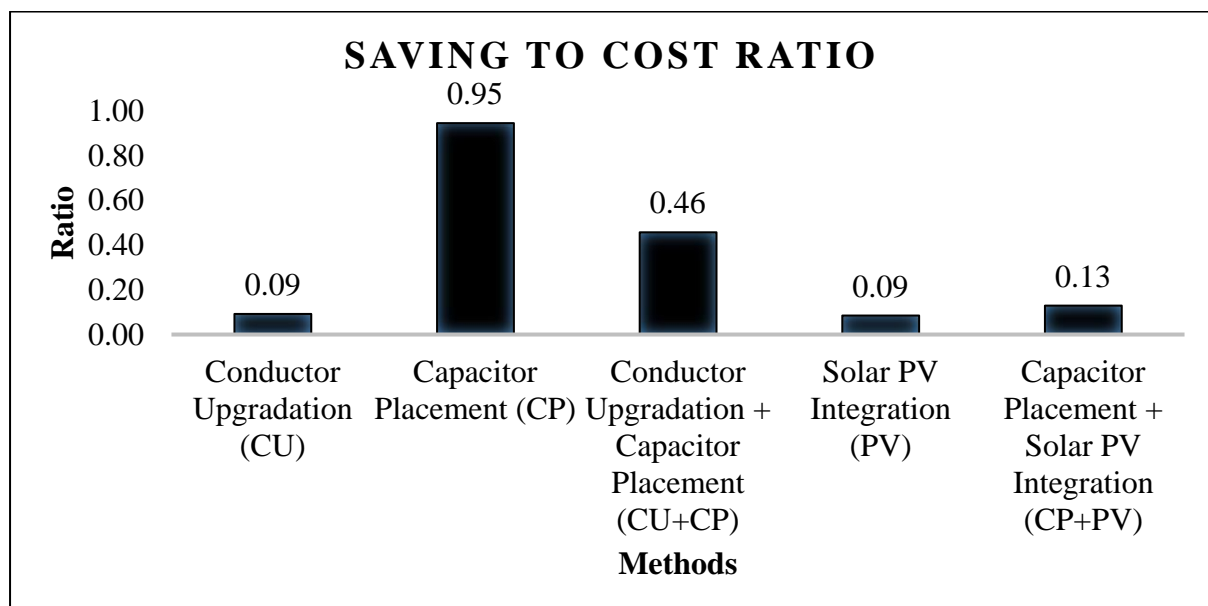


Figure 4.13 Savings to Cost Ratio

**Table 4.10 Financial Analysis**

Method	Cost (NPR)	Load Factor	Loss Load Factor (LLF)	Loss (kW)	Energy Loss (Mwh)	Annual Revenue Loss (NPR)	Annual Savings (NPR)	Loss Reduced (kW)	Cost per kW Loss Reduction (NPR/kW)	Saving to Cost Ratio
Base Case	-	0.66	0.48	409	1721.48	16,732,814.40				
Conductor Upgradation (CU)	6,703,988.80	0.66	0.48	394	1658.34	16,119,141.50	613,672.90	15.00	446,932.59	0.09
Capacitor Placement (CP)	5,280,000.00	0.66	0.48	287	1207.98	11,741,608.15	4,991,206.25	122.00	43,278.69	0.95
Conductor Upgradation + Capacitor Placement (CU+CP)	11,983,988.80	0.66	0.48	275	1157.47	11,250,669.83	5,482,144.57	134.00	89,432.75	0.46
Solar PV Integration (PV)	79,424,932.92	0.66	0.48	243	1022.78	9,941,500.98	6,791,313.42	166.00	478,463.45	0.09
Capacitor Placement + Solar PV Integration (CP+PV)	84,704,932.92	0.66	0.48	141	593.46	5,768,525.26	10,964,289.14	268.00	316,063.18	0.13

Table 4.10 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 0.61, 4.9, 5.4, 6.7, 10.9 million NPR respectively. The Saving to Cost Ratio is found to be 0.09, 0.95, 0.46, 0.09 and 0.13 respectively.

## CHAPTER FIVE : CONCLUSION AND RECOMMENDATION

### 5.1 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 annual savings of 0.61, 4.9, 5.4, 6.7, 10.9 million NPR respectively. The respective Saving to Cost Ratio for various methods was found to be 0.09, 0.95, 0.46, 0.09 and 0.13 respectively.

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.

The research is limited to a single rural 11 kV feeder in Nepal, which may not represent the diversity of distribution networks in other regions or urban settings. The analysis includes specific reinforcement techniques, there may be additional methods not considered in this study which might be more effective. The results obtained are based on certain assumptions made during the study and cannot be generalized.

## **5.2 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 centers. 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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**APPENDIX A : IEEE 10 BUS SYSTEM DATA**

Sending End	Receiving End	Rated kV	Active Power (kW)	Reactive Power (kVar)	Resistance ( $\Omega$ )	Reactance ( $\Omega$ )
1	2	23	1840	460	0.1233	0.4127
2	3	23	980	340	0.014	0.6057
3	4	23	1790	446	0.7463	1.205
4	5	23	1598	1840	0.6984	0.6084
5	6	23	1610	6000	1.9831	1.7276
6	7	23	780	110	0.9053	0.7886
7	8	23	1150	60	2.0552	1.164
8	9	23	980	130	4.7943	2.716
9	10	23	1640	200	5.3434	3.0264

## APPENDIX B : IEEE 33 BUS SYSTEM DATA

S.N.	Sending Bus	Receiving Bus	Rated kV	Active Power (kW)	Reactive Power (kVar)	Resistance ( $\Omega$ )	Reactance ( $\Omega$ )
1	0	1	12.66	100	60	0.0922	0.047
2	1	2	12.66	90	40	0.493	0.2511
3	2	3	12.66	120	80	0.366	0.1864
4	3	4	12.66	60	30	0.3811	0.1941
5	4	5	12.66	60	20	0.819	0.707
6	5	6	12.66	200	100	0.1872	0.6188
7	6	7	12.66	200	100	1.7114	1.2351
8	7	8	12.66	60	20	1.03	0.74
9	8	9	12.66	60	20	1.04	0.74
10	9	10	12.66	45	30	0.1966	0.065
11	10	11	12.66	60	35	0.3744	0.1238
12	11	12	12.66	60	35	1.468	1.155
13	12	13	12.66	120	80	0.5416	0.7129
14	13	14	12.66	60	10	0.591	0.526
15	14	15	12.66	60	20	0.7463	0.545
16	15	16	12.66	60	20	1.289	1.721
17	16	17	12.66	90	40	0.732	0.574
18	1	18	12.66	90	40	0.164	0.1565
19	18	19	12.66	90	40	1.5042	1.3554
20	19	20	12.66	90	40	0.4095	0.4784
21	20	21	12.66	90	40	0.7089	0.9373
22	2	22	12.66	90	50	0.4512	0.3083
23	22	23	12.66	420	200	0.898	0.7091
24	23	24	12.66	420	200	0.896	0.7011
25	5	25	12.66	60	25	0.203	0.1034
26	25	26	12.66	60	25	0.2842	0.1447
27	26	27	12.66	60	20	1.059	0.9337
28	27	28	12.66	120	70	0.8042	0.7006
29	28	29	12.66	200	600	0.5075	0.2585
30	29	30	12.66	150	70	0.9744	0.963
31	30	31	12.66	210	100	0.3105	0.3619
32	31	32	12.66	60	40	0.341	0.5302

**APPENDIX C : 11 kV PRACTICAL FEEDER DATA**

11 kV Padajungi Feeder

Bus Data			Branch Data					
Bus No.	P load (MW)	Q load (Mvar)	From Bus	To Bus	Base Case		Upgradation	
					Resistance (R)	Reactance (X)	Resistance (R)	Reactance (X)
0	0.0000	0.0000	0	1	1.5412	1.9486	1.5412	1.9486
1	0.0000	0.0000	1	2	0.3099	0.3918	0.3099	0.3918
2	0.0783	0.0485	2	3	0.3480	0.2344	0.1759	0.2224
3	0.0196	0.0121	3	4	0.6905	0.4650	0.3490	0.4413
4	0.0196	0.0121	3	5	0.3867	0.2604	0.1954	0.2471
5	0.0000	0.0000	5	6	0.3314	0.2232	0.1675	0.2118
6	0.0391	0.0242	5	7	0.1933	0.1302	0.0977	0.1236
7	0.0195	0.0121	7	8	0.3093	0.2083	0.1564	0.1977
8	0.0391	0.0242	2	9	0.0810	0.1024	0.0810	0.1024
9	0.0195	0.0121	9	10	0.1005	0.1271	0.1005	0.1271
10	0.0388	0.0241	10	11	0.0866	0.1094	0.0866	0.1094
11	0.0387	0.0240	11	12	0.1647	0.2083	0.1647	0.2083
12	0.0385	0.0238	12	13	0.0363	0.0459	0.0363	0.0459
13	0.0000	0.0000	13	14	0.2044	0.1376	0.1033	0.1306
14	0.0384	0.0238	13	15	0.1989	0.1339	0.1005	0.1271
15	0.0768	0.0476	15	16	0.2872	0.1934	0.1452	0.1836
16	0.0768	0.0476	13	17	0.0921	0.1165	0.0921	0.1165
17	0.0383	0.0237	17	18	0.0279	0.0353	0.0279	0.0353
18	0.0000	0.0000	18	19	0.2928	0.1972	0.1480	0.1871
19	0.0382	0.0237	19	20	0.3149	0.2120	0.1591	0.2012

Bus Data			Branch Data					
Bus No.	P load (MW)	Q load (Mvar)	From Bus	To Bus	Base Case		Upgradation	
					Resistance (R)	Reactance (X)	Resistance (R)	Reactance (X)
20	0.0763	0.0473	20	21	0.2762	0.1860	0.1396	0.1765
21	0.0762	0.0472	20	22	0.5469	0.3683	0.2764	0.3495
22	0.0381	0.0236	22	23	0.2486	0.1674	0.1256	0.1589
23	0.0381	0.0236	23	24	0.6076	0.4092	0.3071	0.3883
24	0.0380	0.0236	22	25	0.1878	0.1265	0.0949	0.1200
25	0.0381	0.0236	25	26	0.6076	0.4092	0.3071	0.3883
26	0.0000	0.0000	26	27	0.1160	0.0781	0.0586	0.0741
27	0.0190	0.0118	27	28	0.4088	0.2753	0.2066	0.2612
28	0.0190	0.0118	26	29	0.1712	0.1153	0.0866	0.1094
29	0.0190	0.0118	29	30	0.2431	0.1637	0.1228	0.1553
30	0.0190	0.0118	30	31	0.4088	0.2753	0.2066	0.2612
31	0.0190	0.0118	31	32	0.2928	0.1972	0.1480	0.1871
32	0.0190	0.0118	31	33	0.5248	0.3534	0.2652	0.3354
33	0.0190	0.0118	18	34	0.2262	0.2859	0.2262	0.2859
34	0.0000	0.0000	34	35	0.3370	0.2269	0.1703	0.2153
35	0.0380	0.0235	35	36	0.2652	0.1786	0.1340	0.1694
36	0.0190	0.0118	34	37	0.3658	0.4624	0.3658	0.4624
37	0.0752	0.0466	37	38	0.2597	0.3283	0.2597	0.3283
38	0.0750	0.0465	38	39	0.2429	0.3071	0.2429	0.3071
39	0.0375	0.0232	39	40	0.6132	0.4129	0.3099	0.3918

Bus Data			Branch Data					
Bus No.	P load (MW)	Q load (Mvar)	From Bus	To Bus	Base Case		Upgradation	
					Resistance (R)	Reactance (X)	Resistance (R)	Reactance (X)
40	0.0375	0.0232	38	41	0.3591	0.2418	0.1815	0.2295
41	0.0375	0.0232	41	42	0.3093	0.2083	0.1564	0.1977
42	0.0375	0.0232	42	43	0.3591	0.2418	0.1815	0.2295
43	0.0187	0.0116	43	44	0.4474	0.3013	0.2262	0.2859
44	0.0375	0.0232	44	45	0.3646	0.2455	0.1843	0.2330
45	0.0374	0.0232	38	46	0.0586	0.0741	0.0586	0.0741
46	0.0188	0.0116	46	47	0.1089	0.1377	0.1089	0.1377
47	0.0375	0.0232	47	48	0.1591	0.2012	0.1591	0.2012
48	0.0188	0.0116	47	49	0.1647	0.2083	0.1647	0.2083
49	0.0187	0.0116	49	50	0.2792	0.3530	0.2792	0.3530
50	0.0749	0.0464	50	51	0.2541	0.1711	0.1284	0.1624
51	0.0187	0.0116	51	52	0.2099	0.1414	0.1061	0.1341
52	0.0375	0.0232	52	53	0.8120	0.5468	0.4104	0.5189
53	0.0187	0.0116	37	54	0.0754	0.0953	0.0754	0.0953
54	0.0376	0.0233	37	55	0.1256	0.1589	0.1256	0.1589
55	0.1125	0.0697	55	56	0.1368	0.1730	0.1368	0.1730
56	0.0000	0.0000	56	57	0.0939	0.0632	0.0475	0.0600
57	0.0374	0.0232	56	58	0.1033	0.1306	0.1033	0.1306
58	0.0373	0.0231	58	59	0.4088	0.2753	0.2066	0.2612
59	0.0373	0.0231	58	60	0.2234	0.2824	0.2234	0.2824

Bus Data			Branch Data					
Bus No.	P load (MW)	Q load (Mvar)	From Bus	To Bus	Base Case		Upgradation	
					Resistance (R)	Reactance (X)	Resistance (R)	Reactance (X)
60	0.0744	0.0461	60	61	0.4364	0.2939	0.2206	0.2789
61	0.0372	0.0231	60	62	0.2569	0.3248	0.2569	0.3248
62	0.0371	0.0230	62	63	0.3480	0.2344	0.1759	0.2224
63	0.0185	0.0115	63	64	0.5524	0.3720	0.2792	0.3530
64	0.0185	0.0115	62	65	0.6684	0.4501	0.3378	0.4271
65	0.0741	0.0459	62	66	0.6076	0.4092	0.3071	0.3883
66	0.0000	0.0000	66	67	0.2762	0.1860	0.1396	0.1765
67	0.0184	0.0114	67	68	0.2265	0.1525	0.1145	0.1447
68	0.0184	0.0114	68	69	0.0884	0.0595	0.0447	0.0565
69	0.0184	0.0114	67	70	0.3646	0.2455	0.1843	0.2330
70	0.0184	0.0114	70	71	0.3646	0.2455	0.1843	0.2330
71	0.0368	0.0228	70	72	0.1602	0.1079	0.0810	0.1024
72	0.0000	0.0000	72	73	0.3480	0.2344	0.1759	0.2224
73	0.0368	0.0228	73	74	0.5573	0.2292	0.3314	0.2232
74	0.0184	0.0114	74	75	0.7338	0.3018	0.4364	0.2939
75	0.0184	0.0114	72	76	0.3808	0.1566	0.2265	0.1525
76	0.0368	0.0228	76	77	0.8174	0.3362	0.4861	0.3274
77	0.0184	0.0114	66	78	0.9225	0.6212	0.4663	0.5895
78	0.0366	0.0227	78	79	0.7071	0.4762	0.3574	0.4518
79	0.0183	0.0113	79	80	0.3065	0.1261	0.1823	0.1228

Bus Data			Branch Data					
Bus No.	P load (MW)	Q load (Mvar)	From Bus	To Bus	Base Case		Upgradation	
					Resistance (R)	Reactance (X)	Resistance (R)	Reactance (X)
80	0.0183	0.0113	80	81	0.3623	0.1490	0.2154	0.1451
81	0.0366	0.0227	81	82	0.9289	0.3820	0.5524	0.3720
82	0.0183	0.0113	78	83	0.6353	0.4278	0.3211	0.4060
83	0.0365	0.0226	83	84	0.2375	0.1600	0.1201	0.1518
84	0.0728	0.0451	84	85	0.6518	0.4390	0.3295	0.4165
85	0.0000	0.0000	85	86	0.6850	0.4613	0.3462	0.4377
86	0.0363	0.0225	86	87	0.3480	0.2344	0.1759	0.2224
87	0.0363	0.0225	85	88	0.2541	0.1711	0.1284	0.1624
88	0.0181	0.0112	88	89	0.4309	0.2902	0.2178	0.2753
89	0.0181	0.0112	89	90	0.5469	0.3683	0.2764	0.3495
90	0.0181	0.0112	88	91	0.7789	0.5245	0.3937	0.4977
91	0.0000	0.0000	91	92	0.2707	0.1823	0.1368	0.1730
92	0.0181	0.0112	91	93	0.1823	0.1228	0.0921	0.1165
93	0.0181	0.0112	93	94	0.5027	0.3385	0.2541	0.3212
94	0.0181	0.0112	94	95	0.5524	0.3720	0.2792	0.3530
95	0.0180	0.0112	95	96	0.6595	0.2712	0.3922	0.2641
96	0.0000	0.0000	96	97	0.7617	0.3132	0.4530	0.3050
97	0.0360	0.0223	96	98	0.5388	0.2216	0.3204	0.2158
98	0.0180	0.0111	98	99	0.7060	0.2903	0.4198	0.2827
99	0.0359	0.0223	99	100	0.5759	0.2368	0.3425	0.2306

Bus Data			Branch Data					
Bus No.	P load (MW)	Q load (Mvar)	From Bus	To Bus	Base Case		Upgradation	
					Resistance (R)	Reactance (X)	Resistance (R)	Reactance (X)
100	0.0000	0.0000	100	101	0.4645	0.1910	0.2762	0.1860
101	0.0392	0.0243	101	102	1.0311	0.4240	0.6132	0.4129
102	0.0180	0.0111	100	103	1.0218	0.4202	0.6076	0.4092
103	0.0180	0.0111	99	104	1.0497	0.4317	0.6242	0.4204
104	0.0359	0.0223	104	105	0.6502	0.2674	0.3867	0.2604
105	0.0180	0.0111						

#### APPENDIX D: BUS VOLTAGE PERCENTAGE

Bus ID	Nominal kV	Base Case	Conductor Upgradation (CU)	Capacitor Placement (CP)	CU + CP	Solar PV Integration (PV)	CP + PV
0	11	100	100	100	100	100	100
1	11	92	92.01	95.54	95.56	93.46	97.16
2	11	90.4	90.41	94.68	94.71	92.14	96.61
3	11	90.34	90.37	94.62	94.67	92.08	96.54
4	11	90.32	90.36	94.6	94.66	92.06	96.53
5	11	90.29	90.34	94.57	94.64	92.03	96.5
6	11	90.28	90.33	94.55	94.63	92.01	96.48
7	11	90.28	90.33	94.55	94.63	92.02	96.48
8	11	90.26	90.32	94.54	94.62	92	96.47
9	11	90.02	90.03	94.48	94.51	91.83	96.49
10	11	89.54	89.55	94.24	94.28	91.44	96.35
11	11	89.13	89.14	94.05	94.08	91.11	96.24
12	11	88.36	88.38	93.68	93.72	90.5	96.03
13	11	88.2	88.21	93.6	93.64	90.36	95.99
14	11	88.19	88.2	93.59	93.64	90.35	95.98
15	11	88.18	88.2	93.58	93.63	90.34	95.97
16	11	88.16	88.19	93.57	93.62	90.33	95.96
17	11	87.79	87.81	93.42	93.46	90.04	95.9
18	11	87.67	87.69	93.37	93.41	89.95	95.87
19	11	87.52	87.59	93.29	93.38	89.79	95.8
20	11	87.36	87.49	93.22	93.37	89.64	95.73
21	11	87.35	87.48	93.21	93.36	89.62	95.71
22	11	87.15	87.35	93.15	93.37	89.43	95.67

Bus ID	Nominal kV	Base Case	Conductor Upgradation (CU)	Capacitor Placement (CP)	CU + CP	Solar PV Integration (PV)	CP + PV
23	11	87.12	87.34	93.13	93.35	89.4	95.64
24	11	87.09	87.32	93.1	93.33	89.37	95.61
25	11	87.11	87.33	93.11	93.34	89.38	95.63
26	11	87	87.26	93	93.27	89.27	95.52
27	11	86.99	87.25	93	93.27	89.27	95.51
28	11	86.98	87.25	92.99	93.26	89.26	95.5
29	11	86.97	87.24	92.98	93.26	89.25	95.5
30	11	86.95	87.23	92.96	93.24	89.23	95.47
31	11	86.92	87.21	92.93	93.22	89.2	95.44
32	11	86.91	87.2	92.92	93.22	89.19	95.43
33	11	86.9	87.2	92.91	93.22	89.18	95.43
34	11	86.85	86.86	92.99	93.03	89.32	95.7
35	11	86.82	86.85	92.96	93.02	89.3	95.68
36	11	86.82	86.84	92.96	93.01	89.29	95.67
37	11	85.55	85.57	92.41	92.46	88.35	95.46
38	11	85.31	85.32	92.3	92.35	88.11	95.35
39	11	85.27	85.29	92.27	92.32	88.07	95.32
40	11	85.24	85.27	92.23	92.3	88.04	95.29
41	11	85.22	85.27	92.21	92.29	88.02	95.27
42	11	85.17	85.23	92.16	92.26	87.97	95.22
43	11	85.12	85.2	92.11	92.23	87.92	95.17
44	11	85.07	85.17	92.07	92.2	87.87	95.13
45	11	85.05	85.16	92.05	92.19	87.86	95.11
46	11	85.28	85.3	92.3	92.35	88.08	95.36

Bus ID	Nominal kV	Base Case	Conductor Upgradation (CU)	Capacitor Placement (CP)	CU + CP	Solar PV Integration (PV)	CP + PV
46	11	85.28	85.3	92.3	92.35	88.08	95.36
47	11	85.24	85.26	92.32	92.37	88.04	95.38
48	11	85.24	85.25	92.31	92.36	88.04	95.37
49	11	85.2	85.22	92.35	92.4	88	95.42
50	11	85.14	85.15	92.29	92.34	87.94	95.35
51	11	85.12	85.14	92.27	92.33	87.92	95.33
52	11	85.11	85.13	92.26	92.32	87.91	95.32
53	11	85.08	85.12	92.24	92.31	87.89	95.3
54	11	85.55	85.56	92.41	92.46	88.35	95.46
55	11	85.25	85.27	92.24	92.29	88.16	95.39
56	11	84.95	84.97	92.07	92.12	87.97	95.35
57	11	84.94	84.96	92.07	92.12	87.97	95.34
58	11	84.73	84.75	91.95	92.01	87.84	95.32
59	11	84.71	84.73	91.93	91.99	87.82	95.3
60	11	84.28	84.3	91.73	91.79	87.59	95.28
61	11	84.26	84.29	91.71	91.77	87.57	95.26
62	11	83.82	83.84	91.52	91.58	87.35	95.29
63	11	83.8	83.83	91.5	91.57	87.33	95.28
64	11	83.79	83.82	91.49	91.56	87.31	95.26
65	11	83.75	83.79	91.45	91.54	87.28	95.23
66	11	83.08	83.37	91.1	91.42	87.12	95.37
67	11	82.99	83.31	91.02	91.36	87.03	95.29
68	11	82.98	83.31	91.01	91.35	87.02	95.27
69	11	82.98	83.3	91.01	91.35	87.02	95.27

Bus ID	Nominal kV	Base Case	Conductor Upgradation (CU)	Capacitor Placement (CP)	CU + CP	Solar PV Integration (PV)	CP + PV
70	11	82.9	83.26	90.94	91.31	86.95	95.2
71	11	82.9	83.25	90.93	91.3	86.94	95.19
72	11	82.88	83.24	90.91	91.29	86.92	95.18
73	11	82.84	83.22	90.87	91.27	86.88	95.14
74	11	82.81	83.2	90.85	91.25	86.86	95.12
75	11	82.8	83.19	90.83	91.24	86.84	95.1
76	11	82.85	83.22	90.88	91.27	86.89	95.15
77	11	82.83	83.21	90.86	91.26	86.88	95.13
78	11	82.24	82.84	90.52	91.12	87.06	95.52
79	11	82.15	82.78	90.43	91.07	86.97	95.43
80	11	82.12	82.76	90.41	91.05	86.94	95.4
81	11	82.09	82.74	90.38	91.03	86.92	95.38
82	11	82.07	82.73	90.36	91.02	86.9	95.36
83	11	81.78	82.55	90.24	91	87.14	95.73
84	11	81.62	82.45	90.15	90.96	87.18	95.83
85	11	81.26	82.22	89.95	90.89	87.37	96.14
86	11	81.22	82.19	89.92	90.87	87.33	96.11
87	11	81.21	82.19	89.91	90.86	87.32	96.1
88	11	81.13	82.14	89.89	90.87	87.24	96.09
89	11	81.11	82.12	89.87	90.86	87.22	96.07
90	11	81.09	82.11	89.86	90.85	87.2	96.05
91	11	80.79	81.92	89.77	90.85	86.92	95.98
92	11	80.79	81.92	89.76	90.85	86.91	95.98
93	11	80.72	81.88	89.7	90.81	86.84	95.91

Bus ID	Nominal kV	Base Case	Conductor Upgradation (CU)	Capacitor Placement (CP)	CU + CP	Solar PV Integration (PV)	CP + PV
94	11	80.53	81.76	89.51	90.69	86.66	95.74
95	11	80.34	81.63	89.33	90.58	86.47	95.56
96	11	80.15	81.51	89.15	90.46	86.29	95.38
97	11	80.11	81.48	89.11	90.43	86.25	95.34
98	11	80.02	81.42	89.02	90.37	86.16	95.26
99	11	79.86	81.32	88.88	90.28	86.02	95.12
100	11	79.81	81.28	88.82	90.24	85.96	95.06
101	11	79.77	81.26	88.79	90.22	85.93	95.03
102	11	79.75	81.24	88.77	90.2	85.9	95.01
103	11	79.78	81.27	88.8	90.22	85.94	95.04
104	11	79.79	81.27	88.81	90.23	85.94	95.05
105	11	79.77	81.26	88.79	90.22	85.93	95.03