A TECHNIQUE FOR OPTIMAL CAPACITOR PLACEMENT IN POWER DISTRIBUTION NETWORK

by

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ABSTRACT

Transfer of electric energy from the source of generation to the customer via the transmission and distribution networks is accompanied by losses. The majority of these losses occur in the distribution system. It is widely recognized that placement of shunt capacitors on the distribution system can lead to a reduction in power losses.

Reduction of I^2R loss in distribution systems is very essential to improve the overall efficiency of power delivery. The voltage at different buses/sections of a distribution network improves significantly due to appropriate placement of shunt capacitors. The I^2R loss can be separated into two parts based on the active and reactive components of branch currents. This thesis work presents a method of improving voltage profile and minimizing the loss associated with the reactive component of branch currents by placing shunt capacitors.

This method first determines a sequence of nodes to be compensated by capacitors. The size of the optimal capacitor at the compensated nodes is then determined by optimizing the loss saving with respect to the cost of investment. The performance of the proposed method is investigated on distribution systems consisting of IEEE 9 bus, IEEE 15 bus and IEEE 34 bus radial network. It is found that voltage at each nodes can be maintained within ±10 % of rated voltage and a significant loss saving can be achieved by placing optimal capacitors in the system.

The changing load condition in different seasons of the year is considered. The variable loading condition scenario is implemented considering winter off peak as the minimum loading and summer peak as the maximum loading condition. Comparison with other reported techniques show that the proposed technique obtains a better performance.

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List of Abbreviations

ABC	Artificial Bee Colony
AMFA	Adoptive Modified Firefly Algorithm
DE	Differential Evaluation
DG	Distributed Generation
FA	Firefly Algorithm
FPA	Flower Pollination Algorithm
FR	Fuzzy Reasoning
GA	Genetic Algorithm
HBMO	Honey Bee Mating Optimization
LSF	Loss Sensitivity Factor
NPV	Net Present Value
PGSA	Plant Growth Simulation Algorithm
PLI	Power Loss Indices
PS	Pattern Search
PSO	Particle Swarm Optimization
RCGA	Real Coded Genetic Algorithm
SA	Simulating Annealing
TA	Tabu Search
THD	Total Harmonic Distortion
TLBO	Teaching Learning Based Optimization

Chapter 1

INTRODUCTION

1.1 Introduction

Distribution power loss and poor voltage profile are two major operational problems for distribution utilities. Long distance of radial structure and high R/X ratio aggravates this situation further. In power system the effect of real and reactive power losses are very important. Therefore the computations of these losses are necessary. These losses can be determined by using load flow analysis. The voltage at all the nodes is also found by using load flow. After computing real and reactive power losses it is very necessary to minimize it; because due to these losses considerable amount of power is wasted. Minimizing these losses will improve the system efficiency.

For losses minimizing these and improve the voltage stability of the distribution system, reactive power compensation, use of distributed generation unit, and feeder reconfiguration are used. Reactive power losses are the main reason of major losses so it is necessary to minimize these losses. By using shunt capacitor, reactive power compensation may be done and these losses can be minimized.

Reactive power injection by shunt capacitors reduces demand current and line losses, improves power factor and voltage profile, and increases available capacity of feeders. By using the shunt capacitor the chance of voltage collapse also get reduced. When there are some large or small disturbances occur in a system the voltage will fall and if the voltage will fall sharply, the voltage collapse will occur, causing voltage instability. By installing capacitor at proper location, reactive power is supplied and there is no sharp fall of voltage and no voltage collapse.

The capacitor raises the voltage at the nodes and improves voltage stability. It also improves the power factor the system by providing extra reactive power. These benefits are possible when the capacitors are placed at proper location and of proper size. So it is very important to determine the optimal location and size of capacitor. These benefits are not possible if capacitor is not installed at proper location and it also increase losses and deteriorate the system performances.

1.2 Thesis Motivation

Active power (P) is the energy converted into useful work. Apparent power (S)is the total energy consumed by a load or delivered by the utility. The power that is not converted into useful work is called reactive power (Q). However, this power is needed in order to generate the magnetic field in inductors, motors, and transformers. Nevertheless, it's undesirable because it causes a low power factor. A low power factor means a higher apparent power, which translates into excessively high current flows and inefficient use of electrical power. These currents cause elevated losses in transmission lines, excess voltage drop, and poor voltage regulation.

Improving power factor can reduce system and conductor losses, boost voltage levels, and free up capacity. However, improper techniques can result in over-correction, under-correction, and/or harmonic resonance. The most common method for improving power factor is to add capacitors banks to the system. Capacitors are attractive because they're economical and easy to maintain with no moving parts. They are also electrically very efficient so their use on a network makes no significant increase in the active power requirement from the supply authority.

Generally, real power loss draws more attention as it reduces the efficiency of distributing energy to customers. Nevertheless, reactive power loss is obviously not less important. This is due to the fact that reactive power flow in the system needs to be maintained at a certain amount for sufficient voltage level. Consequently, reactive power makes it possible to transfer real power through transmission and distribution lines to customers. Improvement of voltage profile by strategically placed shunt capacitors in the network feeder can also result in system loss reduction if this requirement is considered in the solution methodology.

Understanding the process for determining the correct methods of sizing capacitors for various applications is important for calculating the values of system and conductor losses, power factor improvement, voltage boost, and freed-up system capacity (kVA).

1.3 Literature Review

Power distribution network is a collection of radial feeders which are inter-connected or grouped with each other by using various tie-switches and tie-lines. The critical issue of electric distribution system is power loss reduction and voltage profile improvement in the grid system. These problems can be rectified by adequate injection of reactive power in the distribution system. The shunt capacitors banks can be installed for the reactive power compensation. However, improper allocation of the capacitors would deteriorate the characteristic of the distribution system. A proper strategy should be designed for determining the location and size of capacitor banks to improve the voltage profile, power factor and reduction of losses. Not only rectifying above problem but also economic analysis has to be considered while allocation of capacitors in the distribution system.

Distribution networks are directly connected to the consumer and these are most sensitive part as far as system losses are concerned. Loss minimization strategies in distribution network are always an area of special interest for researchers and design engineers. Many researchers have come forward with new techniques to address this problem. The solution techniques for the loss reduction by optimal sizing and placement of capacitor problem are a combinatorial optimization problem which also includes the cost of the capacitor and some real time operation constraints. A lot of literature is available on this topic.

Optimal capacitor placement in distorted distribution networks with different load models using Penalty Free Genetic Algorithm has been proposed in [1]. It is assumes that the load is uniformly distributed along the feeder. They consider only peak kilowatt loss savings with fixed capacitors. Emphasis has been given on careful load modelling.

Flower Pollination Algorithm (FPA) and Loss Sensitivity Factors for optimal sizing and placement of capacitors in radial distribution systems have been proposed in [2]. It addresses application of fixed capacitors to a uniformly distributed load. FPA technique is introduced in this paper in order to minimize the investment cost of new compensation sources and the active power losses with mitigating the voltage profiles for different distribution systems. First the most candidate buses for installing capacitors are suggested using Loss Sensitivity Factors (LSF).

Then the proposed FPA is employed to deduce the locations of capacitors and their sizing from the elected buses.

The capacitor placement problem is a combinatorial optimization problem having an objective function composed of power losses and capacitor installation costs subject to bus voltage constraints. Recently, many approaches have been proposed to solve the capacitor placement problem as a mixed integer programming problem. Capacitor placement method which employing particle swarm optimization (PSO) approaches with operators based on Gaussian and Cauchy probability distribution functions has been used in [3]. Loss sensitivity factors have been used for candidate bus selection.

In [4] Loss sensitivity factors and PGSA for capacitor placement in the distribution system has been proposed. The loss sensitivity factors are used to determine the candidate locations of the buses required for compensation. The PGSA is used to estimate the required level of shunt capacitive compensation at the optimal candidate locations to enhance the voltage profile the system and reduce the active power loss. This method places the capacitors at less number of locations.

The loss minimization in distribution systems has assumed greater significance recently since the trend towards distribution automation will require the most efficient operating scenario for economic viability variations. Studies have indicated that as much as 13% of total power generated is wasted in the form of losses at the distribution level [5].

Schmill [6] developed a basic theory of optimal capacitor placement. He presented his well-known 2/3 rule for the placement of one capacitor assuming a uniform load and a uniform distribution feeder. Duran et al [7] considered the capacitor sizes as discrete variables and employed dynamic programming to solve the problem. Grainger and Lee [8] developed a nonlinear programming based method in which capacitor location and capacity were expressed as continuous variables. Grainger et al [9] formulated the capacitor placement and voltage regulators problem and proposed decoupled solution methodology for general distribution system. Baran and Wu [52, 11] presented a method with mixed integer programming. Sundharajan and Pahwa [12] proposed the genetic algorithm approach to determine the optimal placement of capacitors based on the mechanism of natural selection. The author(s) applied GA technique and construct the objective function which consist of minimization of energy losses as well as cost of the shunt capacitors.

A fuzzy based method has been proposed for identification of probable capacitor nodes of radial distribution system in [13]. Simulated annealing technique has been used for final selection of the capacitor sizes. The method has been applied to different test systems.

In [14] it is shown that capacitor placement in distribution systems can also improve the reliability indices by failure rate reduction. A PSO algorithm was proposed in this paper for optimal capacitor allocation in distribution feeders in order to find the solutions. Here two functions have been proposed to improve the reliability indices of a distribution system. The first one is defined as the sum of reliability cost and investment cost. The second is defined by adding the reliability cost, cost of losses and investment cost.

Prakash and Syduluin paper [15]uses an algorithm that employs Particle Swarm Optimization, a meta heuristic parallel search technique for estimation of required level of shunt capacitive compensation to improve the voltage profile of the system and reduce active power loss. Loss Sensitivity Factors are used to determine the optimum locations required for compensation. This method systematically decides the locations and size of capacitors to realize the optimum sizable reduction in active power loss and significant improvement in voltage profile. The method places capacitors at less number of locations with optimum sizes.

Salama and Chikhani [16] have attempted to formulate the problem in a simple manner, without the use of a sophisticated optimization technique. Laterals are handled by first treating each lateral as a separate feeder. The shunt capacitor location and size is then determined to reduce peak power and energy losses. If the savings for the lateral is zero or negative, no capacitor is placed on that lateral. After determining whether capacitors should be placed on each lateral, the optimum size and location for all the capacitors is determined. The objective function of this proposed method is to minimize the total losses and the cost associated with it while maintain the system voltage within limits. The author(s) uses loss sensitivity factor in which particular node has been determine on which capacitor has to be placed. After determination of particular node, capacitor of proper size has been determined and placed on that particular node.

Chis and Jayaram in [17] has used capacitor placement in distribution system using heuristic search strategies. It describes both shunt capacitors and voltage regulators to keep distribution system voltage profile within the desired limits. The Author(s) firstly selected the sequence of the nodes. For compensating those nodes capacitors placement were done and then the sizing of the capacitors were found for that particular node.

Reddy and Sydulu in [18] presents a power loss based approach to determine suitable capacitor locations and an Index and genetic algorithm based approach for optimal capacitor sizing. Highest suitability of nodes for capacitor placement and the corresponding sizes are determined. The objective function of the approach included the cost of power losses, energy losses and capacitor banks

Baran and Wu in [20] used objective function that consists of the peak power loss reduction, energy loss reduction, and a linear cost of capacitors. Constant voltage is assumed and only fixed capacitors are considered.

Murthy and Ravindra in [21] proposes direct search algorithm for capacitive compensation in radial distribution system. It assumes a fixed load condition and a uniform feeder. A concentrated loadat the end of the feeder is dealt with separately.

Paper [22] shows that total active power loss and improve power factor can be reduced by adding shunt capacitors in the distributed systems. But the harmonics distortion level will be amplified with the installation of shunt capacitors in distributed systems in case there is not proper placement with harmonic consideration. Consequently, this paper proposed a technique to determine capacitors placement and its sizing in distorted distribution systems. Technique proposed in this paper is named as direct search algorithm which helped in determined the placement of the capacitors and sizing. In order to search the proper location harmonic power flow had been connected with the algorithm and size of shunt capacitors. By using such method total active power was decreased and power factor can be increased.

In paper [23] the author proposes a technique which implements the enhanced binary PSO for reducing the power loss in distributed system and optimal capacitor placement in the network. In this work a binary string is used for representing the state of the switches and capacitors in the network.

Ali Hassan [24] develops the technique which is the combination of SA i.e. Simulating Annealing, GA i.e. genetic Algorithm, TS i.e. Tabu Search and combination of GA-SA. For implementation 69 bus power system has been used in this study. The main focus of this work is to solve the problem i.e. how to find out the best suitable location for capacitor placement in distributed system, what should be size and type of the capacitor, how to reduce the objective function along with the load constraints or operational constraints (voltage profile). The author introduces sensitivity analysis method to select the candidate installation locations of the capacitors to reduce the search space of this problem.

Shunt capacitors are used for enhancing the performance of distributed system which leads to the energy efficient distributed system in [25]. The main issue is that how to place the capacitor at an optimal location so that the reduction in energy to peak power loss can be achieved. In this work a 10 bus radial system is considered for implementing the proposed work. MATLAB simulation platform is used for implementing the load flow program. The proposed work is based on the combination of load flow data and fuzzy technique.

Damodar Reddy [51] proposed fuzzy and real coded Genetic Algorithm i.e. (RCGA). Thus proposed method had been used to place the capacitors on the primary feeders of the radial distribution systems. In this paper two stage methodologies had been introduced to solve the capacitor placement problem. In the first stage of the approach, fuzzy had used in order to find the optimal location of the capacitor whereas real coded genetic algorithm had used in the second stage. It helped in finding the size of the capacitors. The sizes of the capacitors corresponding to maximum annual savings are determined. The author proposed a new index called as power loss index through this appropriate allocation of capacitor at each node was determined. For compensating these nodes capacitors placement were done and then the sizing of the capacitors were found for that particular node.

Paper [27] proposes that energy efficient model is capable to reduce the power loss and to balance the voltage profile of the system. This is achieved by installing the shunt capacitor at optimal location in a radial distributed network. The proposed works first of all use the loss sensitivity factor in order to find out the optimal location for installing the shunt capacitor. After finding the optimal location it implements the Ant Bee Colony optimization algorithm which selects the suitable size and type of the shunt capacity.

In [28], the proposed work is a hybrid approach which uses two techniques such as PSO and HBMO i.e. Honey Bee Mating Optimization. This technique efficiently selects the optimal location for capacitor placement in the network along with the number of shunt capacitors in order to reduce the power loss and control the voltage profile of power system. First of all the technique determines the number and size of the shunt capacitor which is going to place in a network then it uses the hybrid technique which is a combination of PSO and HBMO in order to evaluate the number optimal bus capacitors at the optimal sizes. The main reason behind using this hybrid approach is less complexity and simplicity of the technique.

Sultana et al.[29] employed a teaching learning based optimization(TLBO) method for optimal capacitors problem in distribution systems.

From all the proposed methods of different researchers, the location and proper size of capacitor that has to be placed in electric distribution system is a major problem otherwise losses will increase if appropriate size of capacitor is not place at appropriate location. There are different methods which have been suggested by different author(s) through which capacitor can be placed for minimizing the loss. Most of the authors have adopted loss sensitivity factor (LSF) method for identifying the optimal locations of capacitor placement. Very few have proposed methods based on power loss indices (PLI).

For finding of optimum sizing of capacitors, various optimization technique and algorithm has been proposed. They are not just only reducing the loss but also minimizing the total cost associated with energy loss as well as capacitor size. Different methods proposed by different author(s) results in minimizing the losses in distribution system.

In this work, loss sensitivity factor (LSF) is adopted for optimal locations of capacitor.

1.4 Research Objectives

This thesis work presents an improved method for placing of shunt capacitors at most appropriate locations in a distribution network. The objective of this research work is to develop a new and improved technique for optimum capacitor placement to-

a. enhance voltage profile in a power distribution network and

b. minimize power losses in distribution lines under variable loading conditions.

1.5 Methodology

IEEE 9 bus, IEEE 15 bus and IEEE 34 bus radial distribution systems will be considered. Loss sensitivity factors indicating the change of voltage and line loss with respect to change in reactive power injection will be employed. These indexes will be used to rank the buses according to their response characteristics. Injection of reactive power by a capacitor bank may change the rank of buses for placement of the next capacitor. The most responsive buses will be selected first for capacitor bank connection and the ranking will be done again. Reactive power will be injected to next higher ranking bus. Improvement of voltage profile of the network will lead to reduction of line losses. A cost function that includes both the cost of investment and savings through loss reduction will be used to determine size of the capacitor bank and ceiling of investment. The useful life of capacitor bank is assumed to be 5 years. Search for locations for installation of capacitors will be continued until no further loss reduction is possible keeping cost function positive.

The analysis will be done by considering the losses before installing the capacitor and after installing the required capacitor to the distribution network.

1.6 Thesis Organization

The objective of this research work is to develop a technique for optimum capacitor placement in a power distribution network to enhance voltage profile and minimize losses under variable loading conditions.

The overall thesis structure is developed as follows:

Chapter 1. Introduction

In this chapter the thesis go over the main points of the importance of reactive power generation through capacitor bank at optimum location as a method for voltage profile improvement and minimization of losses of radial distribution network. This chapter also provides a brief overview about the background of the research work. It sets the outline of the thesis by explaining the important motivation and present problem which form the basis of the thesis. In addition, the objectives to conduct this research and expected outcomes are also clearly defined.

Chapter 2. Optimum Capacitor Placement and Sizing Techniques

This chapter is a comprehensive review of the literature related to the topics and research objectives. This chapter discusses the current strategies of optimum capacitor placement procedure. It consists of the literature review of the previous researches and findings related to the voltage profile improvement of distribution network by capacitor installation.

Chapter 3. Proposed Optimal Capacitor Placement Technique

It consists of research methodology and research flowchart that have been used for this study.

Chapter 4. Simulation Result of Proposed Methodology

This chapter demonstrates the validation of proposed methodology by simulation of IEEE 9 Bus, 15 bus and 34 bus distribution network in PSAF software.

Chapter 5. Performance Analysis

This chapter brings the superiority of proposed scheme into light compared to the existing methods. Several case studies have been discussed under variable loading condition for different IEEE standard radial distribution network. From the case study it is found that the proposed method provides better result and justify the needs if any further investment is required.

Chapter 6. Conclusions

The research outcomes are summarized in this chapter. The deliberated ideas and theories that are employed in this thesis are highlighted. Recommendations for future work along with the limitations of the thesis are also discussed.

Appendices are provided to supplement the study and analysis presented herein.

Chapter 2

OPTIMUM CAPACITOR PLACEMENT AND SIZING TECHNIQUES

2.1 Introduction

Optimal capacitor placement has been a challenge for power system planners and researchers for many years. There are plenty of published papers where different formulations of the problem along with solution methods have been proposed. Many algorithms and techniques are addressed in literature to deal with the problem of optimal capacitor placement (OCP) and sizing in power distribution systems.

In general, the goal is to find optimal locations and sizes of capacitors such that the cost of total real power/energy loss and that of capacitors is minimized. At the same time, acceptable voltage levels have to be maintained throughout the whole network. When shunt capacitors of proper size are appropriately connected in distribution feeders, reactive power injection by these capacitors can address these problems.

The application of shunt capacitor in distribution feeders has always been an important research area. It is because a portion of power loss in distribution systems could be reduced by adding shunt capacitors to supply a part of the reactive power demands. For this reason, the source of the system does not necessarily have to supply all reactive power demands and losses. Consequently, there is a possibility to decrease the losses associated with the reactive power flow through the branches in the distribution systems. The benefits of capacitor placement in distribution systems are power factor correction, bus voltage regulation, power and energy loss reduction, feeder and system capacity release as well as power quality improvement.

In this chapter optimal capacitor placement methodology is further reviewed.

2.2 Optimum Capacitor Placement Techniques

Review of published research literature on distribution system reliability addresses the various aspects such as maintenance strategies as well as the use of capacitor. However, in recent years many researchers have focused on optimal placement of capacitors for enhancement of reliability. Lot of research work is reported in published literature on optimal capacitor placement with the conventional objective function considering total cost of losses and investments.

The optimal capacitor placement problem is solved by various researchers using ant colony direction, graph search algorithm, genetic algorithm, particle swarm optimization and fuzzy evolutionary program. Since the capacitor banks are added in discrete steps the objective function is not differentiable and capacitor placement problem is mixed integer nonlinear program. Optimal capacitor placement increases the load carrying capacity of the lines which helps to improve the reliability of distribution system.

The majority of the research works reported on optimal placement of capacitor focuses mainly on loss reduction and investment on the objective function and very less work is reported on optimal placement of capacitors for reliability enhancement considering the wider objective function. Some of the reported work on reliability improvement using capacitor is focused on few objective functions with various assumptions and constraints. The effect of placement of capacitor on voltage profile is not addressed by many researchers.

A firefly algorithm is used for optimal capacitor placement problem for distribution system reliability indices like system interruption frequency index, system average interruption duration index and average energy not supplied as discussed in [31]. Author had tested IEEE 34 bus system problem and tested feasibility and effectiveness of the result. In this reliability indices are the sub part of objective function in addition to cost of capacitor and active power losses. However interruption cost depends on failure rate is modified with old methods which are based on assumptions.

Population based approach using ant colony search algorithm for capacitor placement is discussed in [32]. Distribution system of Taiwan Power Company is considered for case study and the results are compared with genetic algorithm and simulated annealing. However problem is identified for symmetrical network only. Paper [33] introduces heuristic optimization technique to determine capacitor placement and sizing in radial distribution network. He compared ant colony, fuzzy logic, genetic algorithm, harmony search, particle swarm optimization, Tabu search, simulated annealing, hybrid methods and other optimization methods and concluded that use of particle swarm optimization is widely used due to fast computation and most beneficial results. Author also give comparison of various heuristic optimization techniques (Sirjani, R et al.).

Loss sensitivity factor is used to determine the candidate buses for optimal capacitor placement for maximum benefit due to savings in feeder losses is discussed in [34]. However author assumed balanced network and planning period as one year only. Reliability of the equipment is not addressed. Paper [35] presents an effective technique to evaluate optimal capacitor bank in a ring distribution system. Author used Heuristic Algorithm as an optimization technique. However paper focuses on to regulate voltages of entire network rather than focusing on power factor and power quality issues in capacitor placement. Optimal capacitor placement implemented practically on Macau medium voltage distribution network for power loss minimization. GUROBI commercial package is used to conduct simulation.NPV analysis had been adopted [36] for cost benefit analysis. Assumptions are absent in the paper, however it looks like the simulation is only for symmetrical network. El-Fergany et al. [37] indicates use of differential evaluation (DE) and pattern search (PS) hybrid method for optimal capacitor allocation. Voltage as constraint, reactive power as constraint and line capacity as constraint is considered whereas power factor and power quality issues are not addressed.

Original Firefly algorithm is modified as Adoptive Modified Firefly Algorithm (AMFA) by Olamaei, J. et al. [38]. AMFA is applied for optimal capacitor placement problem of IEEE 9 bus system and results are compared with Fuzzy, PSO and PGSA methods. Overall losses are reduced by 14.106% and cost saving is 12.974%. However reliability cost is not considered. Rani, D.S. et al. [39] discusses about Adoptive Harmony search algorithm (analogy with music improvisation process) which generates new solution vectors that improves accuracy and convergence rate of harmony search algorithm for optimal capacitor placement. In this case study, forward/backward sweep power flow method is used for real and reactive power evaluations as a load flow study. An algorithm is tested on radial distribution system and results are compared with PSO and PGSA methods. Biography based optimization technology is discussed by Tom, T. et al. [40] for active and reactive power compensation by means of capacitor and DG placement. In addition to voltage constraint power limits and power balance as constraint is also used. Simulation results are shown that BBO technique is also one of the methodology choice for researchers of optimal capacitor placement.

Mahdi Mozaffari Legha et al. [41] discussed about Artificial Bee Colony (ABC) algorithm for capacitor placement to improve the network efficiency. Penalty factor due to voltage violation is introduced in objective function rather than voltage as a constraint. Power factor and Power quality constraints are neglected in simulation process. In Result analysis it observers that voltage profile is improved in capacitor placement by using ABC algorithm.

Simplified direct search algorithm to minimize power loss by means of capacitor placement is discussed in [42]. Total harmonic distortion is considered as constraint, at the same time a component as harmonic power loss is also considered. Harmony search approach [43] discusses that in case of unbalanced distribution system, capacitors can be placed. Harmonic constraint is applied to limit the total harmonic distortion within the limit. In addition to this equality and in equality constraints are also discussed. Power loss is computed with components, fundamental component and Harmonic component. Looking towards objective function, it seems that cost function is influenced by harmonic component whereas other researcher had put the limits while selecting simulation search for the best solution.

Farahani, V. et al.[44] developed branch exchange algorithm for network reconfiguration and joint optimization algorithm for energy loss reduction using capacitor placement. Practical implementation of these algorithms was carried out on two feeders of Sirjan distribution network. However CPU time and number of required iterations are much high as compared to other methods. Paper [45] used cuckoo search algorithm for capacitor allocation in radial distribution system. Proposed approach identifies sizing and placement and takes the final decision for optimum location within the number of buses nominated with minimum number of effective locations and with lesser injected VARs. Mixed integer conic programming approach to find optimal capacitor placement is discussed in[46]. 34bus system and 83 bus system is selected for mixed integer conic programming approach. Power losses and cost of capacitor is the part of objective function. Mixed Integer Conic Formulation is convex optimization problems, which insure that local solution is the global solution. A loss sensitivity factor can be used to calculate the location and fire fly algorithm is used for cost minimization including cost of capacitor and cost of power loss as discussed in [47]. Paper [48] introduces harmony memory for network reconfiguration and capacitor placement.

Neelima, S et al.[49] introduces differential evolution to reduce dimension of power flow equations. Dimension reducing distribution load flow algorithm is developed as first stage of optimal capacitor placement and differential evaluation based algorithm is used as power loss minimization. IEEE 39 bus system is used and results are compared with fuzzy and genetic algorithm. Paper [50] introduces Tabu search strategy for optimal capacitor placement which is Heuristic strategy to find capacitor locations and size for a given radial distribution system.

2.3 Determination of Optimum Location and Size of Capacitor

Various optimization technique such as genetic algorithm, fuzzy logic, particle swarm optimization, PGSA, fire fly, ant colony, artificial intelligence/artificial neural network are used for optimum location and sizing of capacitor.

2.3.1 Identification of Optimum Location

Two methods for optimum capacitor location identification, loss sensitivity factor and power loss index method are discussed in brief.

2.3.1.1Loss Sensitivity Factor

For finding the optimum location for placement of capacitor, generally Loss Sensitivity Factor is used by most of the researcher as found from literature survey. The loss sensitivity factors are calculated from the base caseload flow (that is, without compensation) and the values are arranged in descending order for all the transmission lines of the given system. A vector that holds the respective „„end buses"" of the lines arranged in descending order of the values of the loss sensitivity factors is stored. The bus with inflowing power is the one considered for capacitor placement. The descending order of the loss sensitivity factors will decide the sequence in which the buses are to be considered for compensation.

The constraints that need to be satisfied are listed below.

(i) Shunt capacitors limits

$$Q_{Cmax} \leq Q_{total}$$

Where$Q_{Cmax}$is the largest capacitor size allowed and $Q_{total}$is the total reactive load

(ii) Bus bar voltage limits

$V_{min} \leq V_i \leq V_{max}$, in radial power systems V_{min}= 0.9 and V_{max}=1.1

(iii) Line flow limits

$$Flow_k < Flow_{kmax}$$

Where $Flow_k$ is the power flow in kth-line and $Flow_{kmax}$ is the maximum allowable power flow.

Consider a distribution line with an impedance R+jX and a load of Peff + jQeff connected between „p" and „q" buses as given below

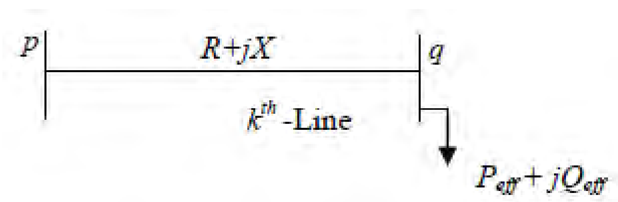


Fig. 2.1: A line connecting two buses

Active power loss in the kth line is given by

$$P_{lineloss}[q] = \frac{(P2_{eff}[q] + Q2eff\,[q])R[k]}{(V[q])2} \qquad (2.1)$$

Similarly the reactive power loss in the k_{th} line is given by

$$Q_{lineloss}[q] = \frac{(P2_{eff}[q] + Q2eff\,[q])X[k]}{(V[q])2} \qquad (2.2)$$

Where, $P_{eff}[q]$ = Total effective active power supplied beyond the node „q".

$Q_{eff}[q]$ = Total effective reactive power supplied beyond the node „q".

Now, Loss Sensitivity Factors can be obtained as shown below:

$$\frac{\partial P_{lineloss}}{\partial Q_{eff}} = \frac{2 \times Q_{eff}[q] \times R[k]}{(V[q])2} \tag{2.3}$$

2.3.1.2 Candidate Node Selection using Loss Sensitivity Factors

The Loss Sensitivity Factors $\frac{\partial P_{lineloss}}{\partial Q_{eff}}$ are calculated from the base case load flows and the values are arranged in descending order for all the lines of the given system. A vector bus position „bpos[i]" is used to store the respective „end" buses of the lines arranged in descending order of the values $\frac{\partial P_{lineloss}}{\partial Q_{eff}}$. The descending order of $\frac{\partial P_{lineloss}}{\partial Q_{eff}}$ elements of "bpos[i]" vector will decide the sequence in which the buses are to be considered for compensation. This sequence is purely governed by the $\frac{\partial P_{lineloss}}{\partial Q_{eff}}$ and hence the proposed „Loss Sensitive Coefficient" factors become very powerful and useful in capacitor allocation or Placement. At these buses of „bpos[i]"vector, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by (norm[i]=V[i]/0.95). Now for the buses whose norm[i] value is less than 1.01 are considered as the candidate buses requiring the Capacitor Placement. These candidate buses are stored in „rank bus" vector. It is worth note that the „Loss Sensitivity factors" decide the sequence in which buses are to be considered for compensation placement and the „norm[i]"decides whether the buses needs Q-Compensation or not. If the voltage at a bus in the sequence list is healthy (i.e., norm[i]>1.01) such bus needs no compensation and that bus will not be listed in the „rank bus" vector. The „rank bus" vector offers the information about the possible potential or candidate buses for capacitor placement.

Chapter 3

PROPOSED OPTIMAL CAPACITOR PLACEMENT TECHNIQUE

3.1 Introduction

Different techniques for optimum capacitor placement have been discussed in chapter 2. These give an insight about the research and advancement going on in this area.

Determination of optimal locations and sizes of shunt capacitors is a complicated combinatorial optimization problem and many different optimization techniques and algorithms have been proposed. Decomposing the location and size determination problem and use of loss sensitivity factor has been suggested. In most of the methods mentioned discussed in chapter 2, loss sensitivity factors (LSFs) has been used to identify candidate buses for capacitor placement, and the loads are considered as time invariant. Moreover, the capacitors are placed in a sequential manner and the impacts of reactive power injected by capacitors that are already placed are not taken into consideration. Injection of reactive power by a capacitor bank changes the reactive power flow in the distribution network and may change the rank of buses for placement of the next capacitor. These issues have been addressed comprehensively in the proposed method. Whenever a capacitor bank is added with the system, the load flow has been carried out to see the impact of introduction of capacitor bank in the system. The loss sensitivity factors have been found to have changed and candidate bus has also been found to have been changed accordingly.

This chapter generally describes the proposed methodology step by step, designing stage, and important parameters and assumptions that are considered.

3.2 Methodology

The problem is decomposed into two major tasks- (i) identification of optimal locations and (ii) determination of capacitor sizes to improve voltage profile. To reduce the search space in optimization procedure for candidate buses selection, sensitivity index indicating the change of voltage and line loss w.r.t change in reactive power injection is employed. These indexes are used to rank the buses according to their response characteristics. Injection of reactive power by a capacitor bank may change the rank of buses for placement of the next capacitor. The most 3(three) responsive buses are selected first for capacitor bank connection and the ranking is done again. Reactive power is then injected to next higher ranking buses. Improvement of voltage profile of the network will lead to reduction of line losses. Several combinations of capacitors are selected and line losses have been determined for each combination of capacitor bank at most responsive buses. The combination of capacitors for which maximum loss is reduced is recorded. The improvement of voltage at each bus is also recorded. These capacitors are added to the system and the load flow is done again to search whether there is any new potential candidate bus. If new bus is identified, capacitors are added and checked for amount of loss reduction and voltage profile improvement at each bus. The search for new buses and addition of capacitors continues until voltages at each bus achieve the minimum value and further loss reduction is not possible.

A cost function that includes both the cost of investment and savings through loss reduction will be used to determine maximum amount of the capacitor bank to be installed and ceiling of investment. The requirement for net savings of investment ensures that the sizing of capacitors are made optimum. The guaranteed useful life of capacitor bank is assumed to be 5 years. Search for locations for installation of capacitors will be continued until no further los reduction is possible keeping cost function positive.

The scenario is simulated for summer peak and winter off-peak conditions. Both fixed and switched type capacitor will be considered. The ratings of fixed capacitors will be decided by the winter off-peak condition. Summer peak will give the maximum reactive power injection conditions part of which will be through fixed capacitors and the rest by switched capacitors.

At first the problem is formulated, then necessary analysis such as load flow, sensitivity, optimum sizing, cost analysis etc. are done to solve the problem.

3.2.1 Problem Formulation

The objective of capacitor placement in the distribution system is to minimize the annual cost of the system. An objective function can be developed to minimize power losses, and minimize cost of capacitor while meeting voltage limit constraints, and enhancement of power factor. Mathematically, the optimal capacitor placement problem can be expressed as follows:

$$\min_{(j,N)} \left(\sum_{p}^{y} P_L yTU + \sum_j (N_j C_{cost,j} + I_{cost,j} + y\, OM_{cost,j})\right) \tag{3.1}$$

subject to, $V_{min} \leq |V_k| \leq V_{max}$

Where,

P_L-Power loss in the network

T - Hours in a year (= 8760)

U - Unit price of electricity

y - No. of year

I_{Cost} - Installation cost/per location

OM_{cost}- Operation and maintenance cost per location per year

C_{cost} - Capacitor cost/kVAr

N- Total compensation requirement at bus j, kVAr

j- Candidate bus for placement of capacitor

i.e. the voltage magnitude at each bus must be maintained within its limits while the cost function is minimized. Solution to (3.1) will give the capacitor location (j), and the value of compensation (N) in kVAr for bus j.

Here, the first part of eqn. 3.1 gives the cost of total energy losses, the second part gives the cost of total capacitor required at all candidate buses, the third part gives the installation cost at all candidate buses, the fourth part gives the operational and maintenance cost at all candidate buses. The time period for each part of eqn. 3.1 is up to year y.

The objective function in (3.1) is an overall cost relating to power loss and capacitor placement. The voltage magnitude at each bus must be maintained between its minimum and maximum voltage limits.

3.2.2 Load Flow Analysis

In this work, load flow solution has been used to determine the power flow in branches and voltages at each node. Initially, the load flow is done without capacitor compensation. Each time capacitor banks are added to any node, a new load flow is carried out to consider the impact of the installed capacitor to find the next candidate location.

3.2.3 Determination of Capacitor Locations

In this work, loss sensitivity factor (LSF) has been employed to identify sensitive bus for capacitor placement.

Real power loss inline *m*, as shown in Figure 3.1, can be expressed as equation (3.2).

$$P_{lossm} = (P_m^2 + Q_m^2)W_m \quad (3.2)$$

Where, $W_m = \frac{r_m}{V_m^2}$

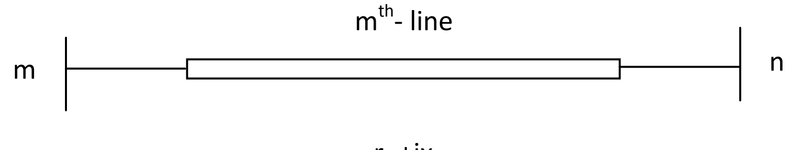


Fig. 3.1 A line connecting two bus of a radial distribution network

Here, r_m is resistance of line m. Line m is connected between bus m and n. P_m and Q_m are active and reactive power, respectively, supplied beyond bus m. V_m is voltage magnitude of bus m. LSF can be calculated for all branches of Figure 3.2 as expressed in equation (3.3).

$$LSF = \frac{\partial P_{lossm}}{\partial Q_m} = \frac{2 \times Q_m \times r_m}{V_m^2} \tag{3.3}$$

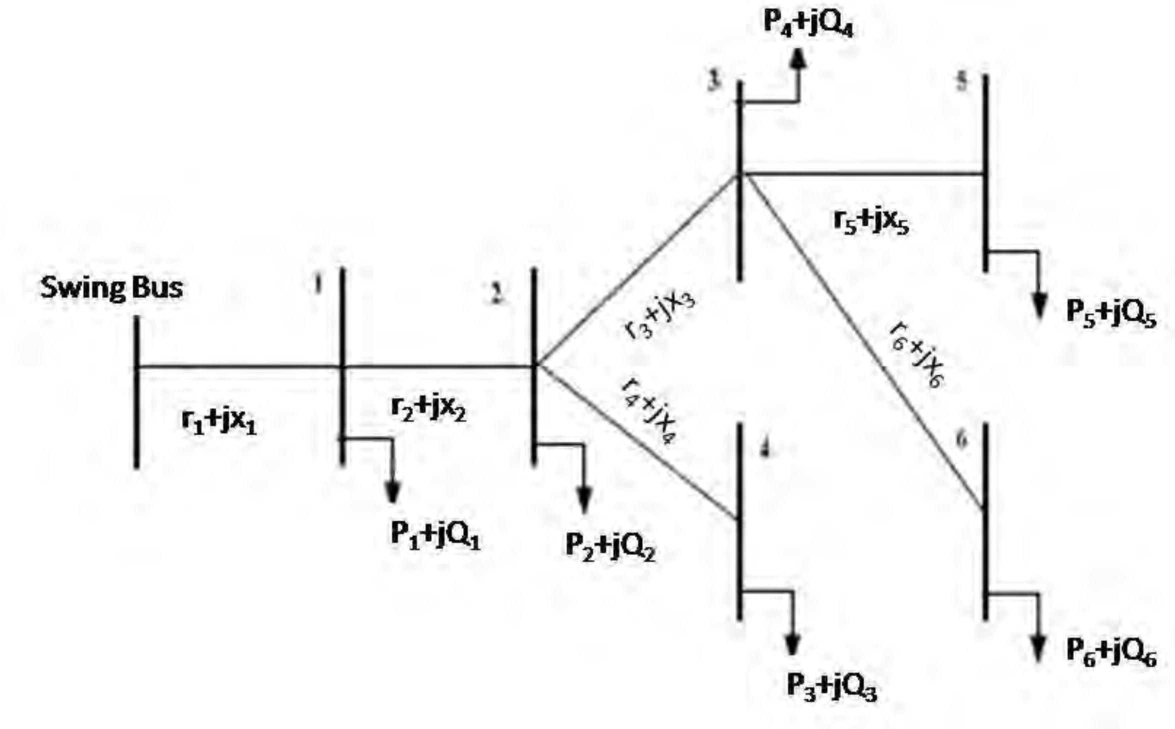


Fig. 3.2Sample diagram of a radial distribution network

LSF helps to reduce the search space. The LSF values are arranged in descending order. Higher values of LSF indicate a sensitive node which is suitable for capacitor placement. Now normalized voltage values can be calculated by using expression (3.4) for each node in the sensitive node list. If normalized voltage value of any node is less than 1.01, then that node needs reactive compensation. LSF decides the sequence of the sensitive nodes and normalized voltage decides whether the node requires reactive compensation or not. If the normalized voltage at sensitive node is greater than 1.01then that particular node can be removed from the sensitive node list since that node voltage is already healthy (within the voltage limits).

$$\text{Normalized Voltage [i]} = \frac{V[i]}{0.95} \tag{3.4}$$

3.2.4 Optimal Sizing of Capacitors

Once capacitors are installed in the radial distribution system, power flows in distribution network gets changed. For example, when two capacitors are installed at 5th and 6th buses, the injected reactive powers will flow through the branches which are connected between capacitors installed buses and the swing bus, this can be observed from Figure 3.3 (with dotted lines). Power flow of the entire system has been affected. Therefore, the total real power loss of the system has been changed.

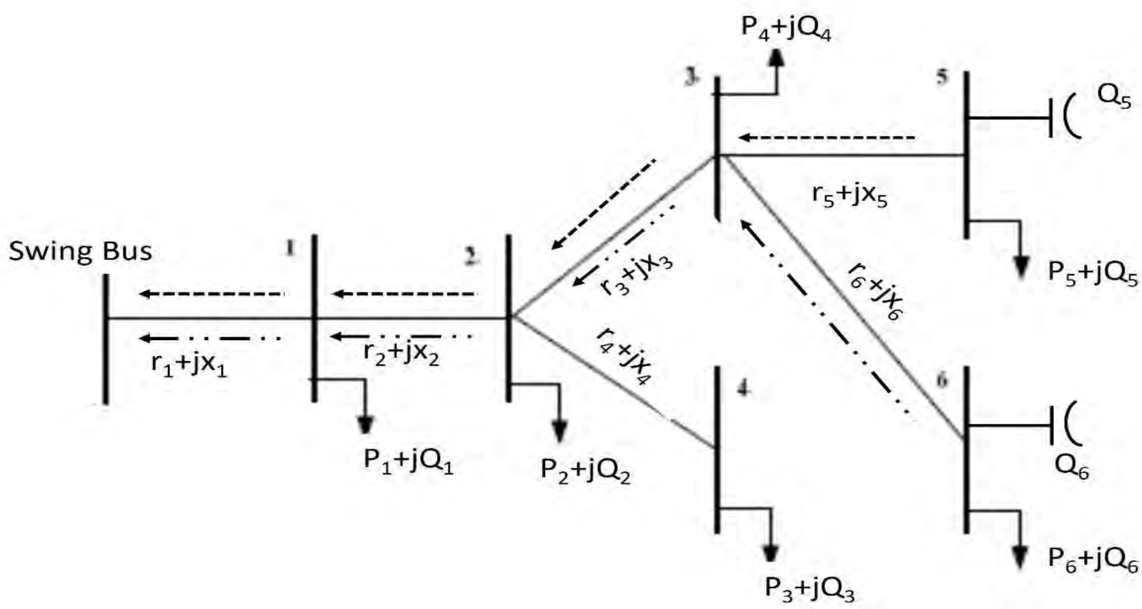


Fig. 3.3 Sample diagram of a radial distribution network with installed capacitor

Total real power loss saving obtained after capacitors installed at optimal locations in the distribution network can be calculated using equation (3.5).

$$\Delta P_L = P_L - P_{Lcap} \tag{3.5}$$

Where,

P_L–Power loss in the network before compensation

$P_{L\text{-}cap}$– Power loss in the network after capacitor compensation

After initial power flow analysis, the most 3(three) responsive buses are selected first for capacitor bank connection. Several combinations of capacitors are selected and line losses have been determined for each combination of capacitor bank at most responsive buses. The combination of capacitors for which maximum loss is reduced is recorded. The improvement of voltage at each bus is also recorded. These capacitors are added to the system and the load flow is done again to search whether there is any new potential candidate bus. If new bus is identified, capacitors are added and checked for amount of loss reduction and voltage profile improvement at each bus. The search for new buses and addition of capacitors continues until voltage at each bus achieves the minimum value and further loss reduction is not possible.

3.3 Cost Analysis

The cost analysis is done to determine the ceiling of investment for which cost function is positive.

The net cost savings can be expressed as:

$$S = E - I \tag{3.6}$$

Where,

E- Net savings = *E1*-*E2*

E1- Energy cost before compensation

E2- Energy cost after compensation

I- Cost of investment

$$E1 = \sum_{p}^{y} P_L yTU \tag{3.7}$$

$$E2 = \sum_{p}^{y} P_{L-cap}\, yTU \tag{3.8}$$

$$I=\sum_{p}^{y}\sum_{j}(N_j\,C_{cost,j} + I_{cost,j} + y\,OM_{cost,j}) \quad (3.9)$$

Where,

P_L- Power loss in the network before compensation

$P_{L\text{-}cap}$- Power loss in the network after capacitor compensation

T- Hours in a year =(8760)

U- Unit price of electricity

y- no. of year for useful life of capacitor

I_{Cost} - Installation cost/per location

OM_{Cost}- Operation and maintenance cost per location per year

C_{cost} - Capacitor cost/kVAr

N- Total compensation requirement at bus j, kVAr

j- Candidate bus for placement of capacitor

3.4Simulation Assumptions

This study focuses on the IEEE 9 Bus, IEEE 15 Bus and IEEE 34 bus radial distribution system. Loss sensitivity factor is used as a tool for selecting candidate buses. The scenario will be simulated for summer peak and winter off-peak conditions. A cost function is also developed to investigate the worthiness of investment for voltage profile improvement. All calculations and analysis are being carried out by PSAF software version-

The following assumptions need to be taken into account:

a) The simulations experiment assumed perfect simulation
b) The values of the capacitor are discrete and randomly selected. Both fixed and switch type capacitor are available.

c) Total capacity of shunt capacitor bank added does not exceed the total reactive power demanded by the system.
d) At first, capacitors are placed in most responsive 2/3 buses. If bus voltages of all section do not achieve the minimum target value, shunt capacitor is placed at next optimum location based on new LSI calculation.
e) The load data available of various IEEE systems is assumed to be data for summer peak demand.
f) Winter off peak load demand is assumed 60% of summer peak demand.
g) Balanced network considered for simplicity
h) Capacitor placement affects only the flow of reactive power in the feeder.

3.5 Designing Stages

1. The main design criteria are to find the optimum location for placement of capacitors and then finalizing the optimum sizes of capacitors for which investment is considered as worthy. To make sure that the proposed solution helps the distribution utility in real scenario, the time variant nature of load during different seasons of the year is considered. In particular, summer peak and winter off peak loading conditions are considered. The corresponding kVAr requirement provides the information for ceiling of maximum and minimum compensation required for the network. Switch type capacitors are proposed to provide flexibility in operation.
2. After running the load flow without adding any capacitor, the various parameters of the system network such as bus voltages, line impedances, line losses, active and reactive power flow through different sections of the network etc. have been recorded. The data of both p.u value and actual value have been recorded for detail analysis. Based on the load flow data, loss sensitivity analyses have been performed and normalized voltage has been calculated. The candidate nodes for the placement of capacitors are determined using the loss sensitivity factors.

Loss sensitivity factor provides information regarding the sequence for placement of capacitor and normalized voltage provides information regarding the candidate nodes that needs capacitor compensation.

The estimation of these candidate nodes basically helps in reduction of the search space for the optimization procedure.

The first three responsive buses are initially considered for placement of capacitor. It is assumed that minimum size of capacitor available is 100 kVAr. At the beginning 100 kVAr is added at each three most responsive bus. Then gradually value of capacitor is increased as long as voltage continues to improve and losses continue to decrease. We stop at that combination of capacitor for which loss reduction is the maximum. Then loss sensitivity factor and normalized voltage is calculated again to determine the new candidate bus. The cost function is also verified to determine whether it remains positive or not. The process is continued until we get our desired capacitor combination that gives minimum required voltage at each bus and loss reduction is maximum keeping cost function positive.

3.6Process Flow Chart

Figure 3.3 shows the overall process flow of this studies:

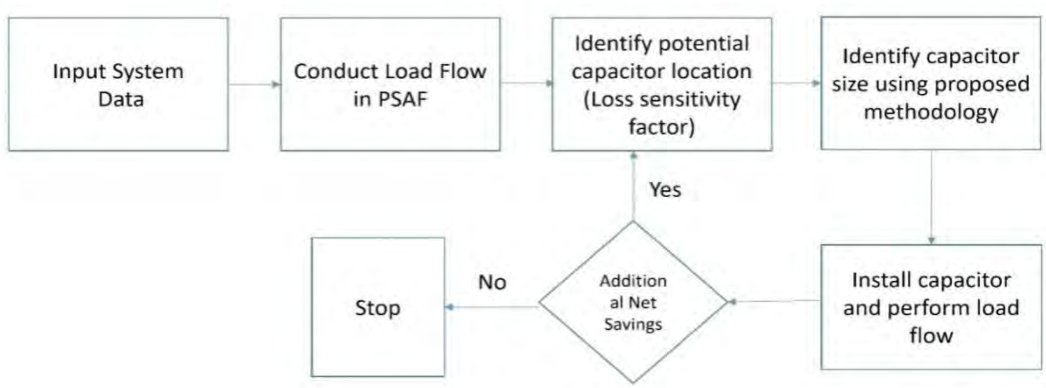


Fig. 3.4 Process flowchart for the proposed technique

Process Sequence:

a. At first, the system data mentioned in Appendix A is inserted as input to the PSAF simulation software and load flow is carried out. The load flow result is exported to MS Excel and Loss sensitivity (LSF) factor is calculated. The buses are arranged in descending order based on the value of LSF. The LSF provides the information regarding the sequence of placement of capacitor. The highest LSF has the highest priority and so on. To minimize search space for potential candidate buses, normalized voltage is calculated. The potential buses for placement of capacitor are then identified from normalized voltage.

b. Initially, capacitor is placed in the most sensitive bus and the impact i.e variation of bus voltage and line losses are observed. The impact is found positive. It is also found that the impact is more i.e. bus voltage improvement and line loss reduction are more promising when placement of capacitor are continued in more than one bus. It is also observed that when capacitor is placed in 4/5 buses or more, line losses increases. Moreover, LSF value and candidate buses for placement of capacitor change. So, initially capacitor is placed in most responsive 3 buses. It is observed that when capacitor is placed in most responsive 3 buses instead of most responsive first 1/2 buses, though the LSF value changes but sequence and candidate buses for placement of capacitor of first 3 bus remain same and the impact is found positive. So, to minimize the search space for optimum location, initially capacitor is placed in first most responsive 3 buses.
c. The sizing is determined based on the value of bus voltage, loss reduction and cost function. The capacitor is continued to be added as long as bus voltages improve, line losses reduces and cost function remains positive.

3.7 Main Scheme of Proposed Methodology

The proposed methodology can be divided into following three major parts:

(i) Identification of optimal locations;

(ii) Determination of optimum capacitor sizes to improve voltage profile; and

(iii) Validating the necessity of capacitor installment at optimum location by using a cost function. A cost function is developed to find the ceiling of maximum investment that will ensure net savings from such initiatives.

3.7.1 Tasks Performed in the Proposed Methodology

Each of above three parts of proposed methodology consists of several specific tasks which are carried out in steps.

Part A: Identification of Optimal Location

Step 1: Modeling of the distribution network using simulation software. The data required for network modeling are listed below.

a. Number of buses.
b. Voltage level of buses
c. Load demand (active (watt) and reactive (VAR) power) at each bus.
d. Bus voltage limits (V_{min}, V_{max}).
e. Distribution lines‟ impedances (resistance and reactance).
f. Length of distribution line
g. Distribution lines‟ capacity (maximum allowable power flow).

Step 2: Perform load flow without capacitor compensation. From the base case load flow the following outputs are recorded:

a. Bus voltage
b. Branch power (active and reactive)
c. Loss in each branch (active and reactive)
d. Power factor

Step 3: Loss Sensitivity Analysis

Sensitivity analysis refers to the determination of how "sensitive" a parameter is to changes in the value of the other parameters of a model or to changes in the structure of the model. It is defined as "ratio Δx/Δy relating small change Δx of some dependent variable to small change Δy of some independent or controllable variable y" . In this study, loss sensitivity is used.

a. The loss sensitivity factors are calculated from the base case load flow (that is, without compensation) and the values are arranged in descending order for all the distribution lines of the given system.
b. A vector that holds the respective „„end buses‟‟ of the lines arranged in descending order of the values of the loss sensitivity factors is stored.

c. The descending order of the loss sensitivity factors will decide the sequence in which the buses are to be considered for compensation.
d. Normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by(norm[i]=V[i]/0.95) .
e. Now for the buses whose norm[i] value isless than 1.01 are considered as the candidate buses requiring the Capacitor Placement. These candidate buses are stored in „rank bus" vector.
f. The final sensitive node list after applying above LSF method needs reactive power compensation, which are selected as optimal locations of capacitor.
g. Once the optimal locations are known, calculate the cost capacitor sizes and corresponding annual net energy savings for given system by using equation (3.10).
h. If significant annual net energy savings are achieved consider one more location of capacitor from the final sensitive node list go to step 5, otherwise stop.

It is worth noting that the „loss sensitivity factors" decide the sequence in which buses are to be considered for compensation placement and the „norm[i]"decides whether the buses needs Q-Compensation or not. If the voltage at a bus in the sequence list is healthy (i.e. $V_{norm}[i]>1.01$) such bus needs no compensation and that bus will not be listed in the „rank bus" vector. The „rank bus" vector offers the information about the possible potential or candidate buses for capacitor placement.

Part B: Determination of Capacitor Size to Improve Voltage Profile

Step 1: From the initial load flow study, the total kVAr requirement of the network and bus voltages at each section has been studied.

Step 2: Initially, top 3 (three) responsive buses from the „rank bus" have been considered for placement of shunt capacitors.

Step 3: Adding of capacitors may change the rank bus. The rank bus is determined each time after adding of shunt capacitors at responsive buses. Adding of capacitor is continued until voltage at all buses achieve the minimum target value i.e 90% of rated value and no further loss reduction is possible keeping cost function positive.

Part C: Justification of Investment

Step 1: A cost function is developed to decide on the optimum size of the capacitor bank and ceiling of investment.

Step 2: Search for locations for installation of capacitors will be continued until no further loss reduction is possible keeping the overall savings through loss reduction greater than the cost of investment for installation of capacitor bank.

Step 3: If bus voltages at all buses are not found to have achieved the required minimum target i.e. 90% of rated value, search for locations for installation of capacitors will be continued and capacitors are installed at optimum locations even though cost function becomes negative. This is done to help utility management taking decision whether to go for further investment in their network or not.

Chapter 4

SIMULATION RESULTS

4.1 Introduction

The proposed methodology has been tested in IEEE 9 bus, IEEE 15 bus and IEEE 34 bus distribution networks using PSAF software platform. The data set for these networks is presented in Appendix A. The following procedure has been followed step by step to implement the proposed methodology.

a. Base case load flow study carried out at first
b. Loss sensitivity factor calculated from base case load flow to determine the sequence through which compensation will be done.
c. V_{norm} voltages calculated to determine the buses that need compensation.
d. Based on the LSI and V_{norm}, compensation is done at first in three most responsive buses. It is observed that when capacitor is placed in most responsive 3 buses instead of most responsive first 1/2 buses, though the LSF value changes but sequence and candidate buses for placement of capacitor of first 3 bus remain same and the impact is found positive i.e. bus voltage improvement and line loss reduction are found more promising. So, to minimize the search space for optimum location, initially capacitor is placed in first most responsive 3 buses. Several combination of capacitor is added until the optimum combination is found which gives maximum loss reduction and beyond which loss increases. The cost function is checked to determine whether investment becomes positive or negative.
e. After adding capacitor at three most responsive buses, LSI and V_{norm} are calculated again to determine the next most responsive buses that need compensation. Then different amount of capacitor is added and the optimum size is calculated from calculating the amount of loss reduced and additional investment required reducing that particular amount of loss.
f. The search is stopped when further loss reduction is not possible keeping cost function positive or additional investment becomes more than the cost of energy saved by placing additional capacitor at the responsive bus.

The main differences of the proposed technique with techniques mentioned in references are:

a. Time variant load is considered.
b. Impact of reactive power injected at a bus is considered.
c. The technique provides utility management an option to decide how much investment shall be considered as worthy investment to improve voltage profile and reduce technical losses.

Load variation is accommodated by considering the two extreme loading conditions, namely, (a) summer peak loading condition, and (b) winter off-peak loading condition. Winter off peak load is assumed to be 60% of summer peak load. For 15 Bus, it is considered as 80% otherwise, the result does not converge. The standard data for the aforementioned three test networks are taken as data set for summer peak load for this research work. The value of capacitors under winter off peak condition is the minimum value of compensation required for the network. These capacitors are considered as fixed capacitors and then switched capacitors are considered to cater the variable loading condition that increases from the winter off peak condition.

The value of capacitor compensation found for summer peak loading condition and winter off peak loading condition are the maximum and minimum capacitor value required for the network. As the loads increase from the minimum loading condition at winter off peak condition to the maximum loading condition at summer peak condition, the LSI changes. In this work, switched type capacitor are proposed for placement of required size of capacitor at the prospective candidate buses based on LSI and normalized bus voltage value. The minimum size of capacitor available is assumed to be 100 kVAr and useful life of capacitor set is assumed to be 5 years.

This chapter presents the simulation result carried out for IEEE 9 bus, IEEE 15 bus and IEEE 34 bus distribution networks. List of different cases considered are presented in Table 4.1

Table: 4.1 List of different cases considered during the simulation

Case	**Description**
IEEE 9 Bus Distribution Network	
Case -1	Summer peak loading condition with no reactive compensation
Case -2	Summer peak loading condition with reactive compensation made at buses 5, 4 & 8
Case -3	Summer peak loading condition with reactive compensation made at buses 5, 4 , 8

Case	Description
	& 6
Case -4	Winter off peak loading condition with no reactive compensation
Case -5(a)	Winter off peak loading condition with reactive compensation made at buses 5, 8&7
Case -5(b)	Winter off peak loading condition with reactive compensation made at buses 5, 8&7
Case -5(c)	Summer peak loading condition with reactive compensation made at buses 5,4,6,7 & 8
IEEE 15 Bus Distribution Network	
Case -6	Summer peak loading condition with no reactive compensation
Case -7	Summer peak loading condition with reactive compensation made at buses 6, 3 & 11
Case -8	Winter off peak loading condition with no reactive compensation
Case -9	Winter off peak loading condition with reactive compensation made at buses 12, 14&15
Case -9(b)	Summer peak loading condition with reactive compensation made at buses 6,3,12, 14&15
IEEE 34 Bus Distribution Network	
Case -10	Summer peak loading condition with no reactive compensation
Case -11	Summer peak loading condition with reactive compensation made at buses 19, 22 & 20
Case -12	Winter off peak loading condition with no reactive compensation

Assumptions considered while calculating the cost for capacitor placementare given in Table 4.2.

Table 4.2 Assumptions considered for cost calculation

Sl. no.	Assumptions	Value
1	Capacitor cost/kVAr/year [BDT][is the value correct]	1000
2	Capacitor installation cost/ per location [BDT]	30,000
3	Operation and maintenance cost per location per year [BDT]	20,000
4	Electricity tariff [BDT/kWh]	6.2
5	Useful life of capacitor [year]	5

4.2 Simulation Result for IEEE 9 Bus System

4.2.1 Summer Peak Loading Condition

The base case load flow study network is shown in Figure 4.1. At first, the IEEE 9 bus distribution network is drawn into the simulation software. Here, connection of the capacitor is shown by the dotted line. It means, under these circumstances, the capacitors are not connected to the network, it is deactivated.

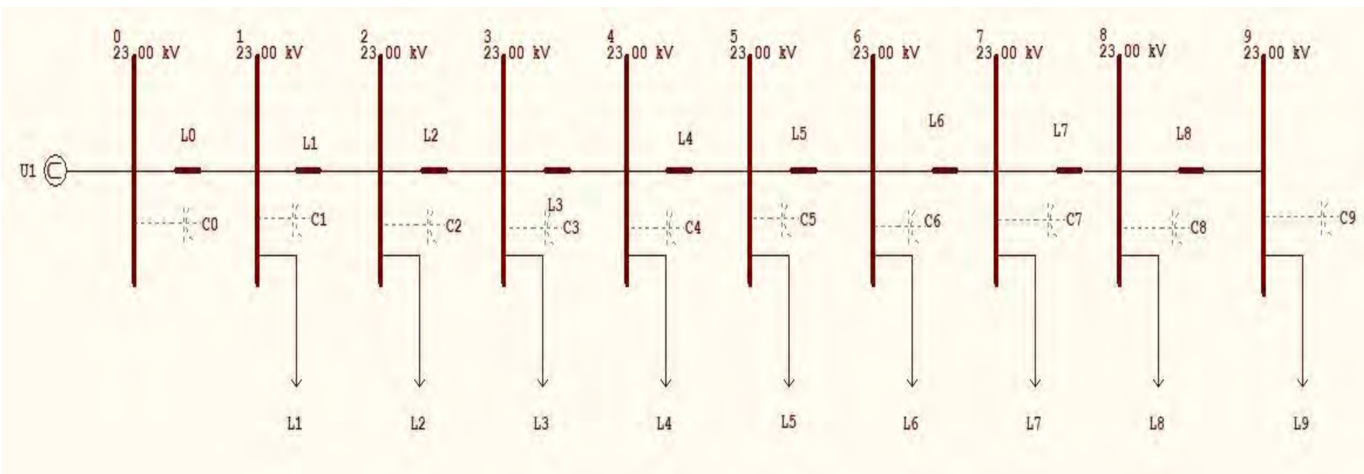


Fig 4.1: IEEE 9 bus distribution network

Case 1

The base case load flow is run without adding any capacitor to the network. From the simulation result, the bus voltage, loads, and line flows are collected and presented in Tables4.3 to 4.5.

Table 4.3: Bus voltages for Case 1

Bus ID	kV Base	V sol[kV]	Ang sol[deg]	Vmin[kV]	Vmax[kV]	P Gen[kW]	Q Gen[kVAr]
0	23	23	0	20.7	25.3	13146.19	5207.45
1	23	22.84	-0.5	20.7	25.3	0	0
2	23	22.71	-1.3	20.7	25.3	0	0
3	23	22.16	-2.3	20.7	25.3	0	0
4	23	21.81	-2.7	20.7	25.3	0	0
5	23	21.1	-3.7	20.7	25.3	0	0
6	23	20.87	-4.1	20.7	25.3	0	0
7	23	20.45	-4.6	20.7	25.3	0	0

Bus ID	kV Base	V sol[kV]	Ang sol[deg]	Vmin[kV]	Vmax[kV]	P Gen[kW]	Q Gen[kVAr]
8	23	19.75	-5.4	20.7	25.3	0	0
9	23	19.27	-6	20.7	25.3	0	0

Table 4.4:Bus loads for Case 1

Load ID	Bus ID	P[kW]	Q[kVAr]	S[kVA]	P. Factor[%]
L1	1	1840	460	1896.63	97
L2	2	980	340	1037.3	94.5
L3	3	1790	446	1844.73	97
L4	4	1598	1840	2437.05	65.6
L5	5	1610	600	1718.17	93.7
L6	6	780	110	787.72	99
L7	7	1150	60	1151.56	99.9
L8	8	980	130	988.58	99.1
L9	9	1640	200	1652.15	99.3

Table4.5: Line flows, line losses, and line loading (%) for Case 1

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L0	0	1	13146.18	5207.42	14139.99	93	354.9	46.61	59.2
L1	1	2	11269.93	4593.94	12170.27	92.6	307.7	3.98	51.3
L2	2	3	10277.76	4082.18	11058.78	92.9	281.1	176.98	46.9
L3	3	4	8326.21	3350.15	8974.92	92.8	233.8	114.57	39
L4	4	5	6620.52	1407.35	6768.45	97.8	179.2	191.08	29.9
L5	5	6	4807.93	641.77	4850.57	99.1	132.8	47.87	22.1
L6	6	7	3974.61	493.55	4005.14	99.2	110.8	75.73	18.5
L7	7	8	2742.62	394.11	2770.79	99	78.2	88.07	13
L8	8	9	1667.91	219.62	1682.31	99.1	49.2	38.76	8.2
Total loss for base case scenario								**783.65**	

Sensitivity analysis

Consider the branch connecting two buses shown in Figure 4.2. The power from sending end bus is P and receiving end bus is Q. Voltages at buses i and j are Vi and Vj, respectively. The line impedance is R+jX. The loss sensitivity factor of such a line is calculated using the following formula:

$$LSF = \frac{\partial P_{loss}}{\partial Q} = \frac{2 \times Q_{ij} \times R_{ij}}{V_i^2} \tag{4.1}$$

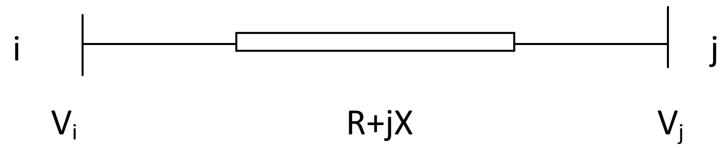


Figure 4.2: A branch connecting two buses

The loss sensitivity factor of each bus is determined by using the above formula. LSI gives the sequence for placement of capacitor. Then normalized voltage is calculated. The normalized voltage value tells which bus needs capacitor compensation. Table 4.6 shows the LSI and normalized voltage values, and identifies the buses that require compensation.

Table 4.6: Loss sensitivity factors arranged in descending order for Case 1

Order	LSI	Start bus	End bus	V_i [p.u.]	V_j [p.u.]	V_{norm} [p.u.]	Compensation required at bus no.
1	0.011875143	2	3	0.987	0.963	1.013684	-
2	0.011679659	4	5	0.948	0.917	0.965263	5
3	0.009680682	3	4	0.963	0.948	0.997895	4
4	0.009175856	7	8	0.889	0.859	0.904211	8
5	0.005475625	8	9	0.859	0.838	0.882105	9
6	0.004722634	6	7	0.907	0.889	0.935789	7
7	0.002442187	5	6	0.917	0.907	0.954737	6
8	0.002424032	0	1	1	0.993	1.045263	-
9	0.000246969	1	2	0.993	0.987	1.038947	-

It is found that the following buses need capacitor compensation in the following sequence: {5,4,8,9,7,6}. The first three most responsive buses {5,4,8} are initially selected for placement of capacitor.

From the load flow data as shown in Table 4.1, it is found that total reactive power in no-compensation scenario is approx. 5200kVAr. Moreover, the buses {7,8,9} do not have the minimum voltage requirement. From Table 4.3, it is found that total loss for base case study is 783.6 kW. So, here objective is to place capacitor at buses {5,4,8} to-

(i) Boost up the voltage at buses {7,8, and 9} so that these buses can have voltage of minimum 20.7 kV; and

(ii) Reduce the losses further from 783.6 kW. However, it is also ensured that the cost function remains positive that is net saving prevails the overall investment required to maintain minimum 20.7 kV voltage at all 9 buses of the IEEE 9 bus network.

Several combination of capacitor is placed at these buses. It is found that the following combination reduces the loss maximum and if further capacitor is added beyond these values, loss is increased.

a. Bus 5: 1500 kVAr
b. Bus 4: 1500 kVAr
c. Bus 8: 1200 kVAr

Case 2

Here the impact of capacitor compensation at buses {5,4,8} is evaluated. Capacitors are placed at the following buses:

a. Bus5 - 1500 kVAr
b. Bus4 - 1500 kVAr
c. Bus8 - 1200 kVAr.

From the simulation result the bus voltage, loads, and line flows are collected and presented in Tables 4.7 and 4.8.

Table 4.7: Bus voltages for Case 2

Bus ID	V sol[kV]	Ang sol[deg]
0	23	0
1	22.91	-0.6
2	22.88	-1.3
3	22.54	-2.7
4	22.29	-3.3
5	21.78	-4.8
6	21.59	-5.3

Bus ID	V sol[kV]	Ang sol[deg]
7	21.24	-6
8	20.7	-7.4
9	20.25	-7.9

Table 4.8: Line flows, line losses, and line loading (%) for Case 2

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L0	0	1	13075.09	1325.79	13142.14	99.5	329.9	40.26	55
L1	1	2	11190.21	718.52	11213.25	99.8	282.6	3.35	47.1
L2	2	3	10238.21	289.46	10242.3	100	258.4	149.51	43.1
L3	3	4	8384.21	-343.63	8391.25	99.9	214.9	96.79	35.8
L4	4	5	6634.46	-894.18	6694.45	99.1	173.4	178.85	28.9
L5	5	6	4803.98	-328.97	4815.23	99.8	127.7	44.26	21.3
L6	6	7	4000.6	-467.97	4027.88	99.3	107.7	71.52	18
L7	7	8	2732.54	-586.79	2794.83	97.8	76	83.02	12.7
L8	8	9	1634.24	199.71	1646.4	99.3	45.9	33.81	7.7
Total								**701.37**	

The loss sensitivity factor of each bus of IEEE 9 bus system is determined and normalized voltage is calculated. Table 4.9shows the LSI and normalized voltage values.

Table 4.9: Loss sensitivity factors for Case 2

Order	LSI	Start bus	End bus	V_i (p.u.)	V_j (p.u.).	V_{norm} (p.u.)	Compensation required at bus no.
1	0.004988099	5	6	0.947	0.939	0.988421	6
2	0.000854997	2	3	0.995	0.98	1.031579	--
3	0.000606008	0	1	1	0.996	1.048421	--
4	3.73563E-05	1	2	0.996	0.995	1.047368	--
5	-0.0008248	3	4	0.98	0.969	1.02	--
6	-0.00114495	8	9	0.9	0.88	0.9263158	9
7	-0.00440624	6	7	0.939	0.923	0.971579	7
8	-0.00718644	4	5	0.969	0.947	0.996842	5
9	-0.01276844	7	8	0.923	0.9	0.947368	8

From simulation data we see that total loss is 701.37 kW and only bus no. 9 is falling behind the minimum voltage requirement. Addition of capacitor has increased the voltage of all buses and only 1 bus is left behind out of 3 buses from minimum voltage requirement. Moreover, total losses have also been decreased by nearly 80 kW. After checking with the cost function, it is found that net savings remains positive. So, we can continue adding capacitor in the most responsive bus to boost up voltage at bus 9.

From new loss sensitivity factor, it is found that a new set of buses are found which needs capacitor compensation. The most responsive bus is now found to be bus no. 6. So, next capacitor compensation is done t bus no. 6. Initially 100 kVAr is added and found that voltage at bus 9 increases and total loss continues to decrease. So, value of capacitor compensation is continued till voltage at all buses reach minimum value. When 1000 kVAr is added at buses 6, it is found that voltage at bus 9 reaches the minimum requirement that is 20.7 kV and total loss is 685 kW. When we add the next 100 kVAr set with the 1000 kVAr set that is total 1100 kVAr is added, we see that losses increases from 685 kW. So, maximum capacitor added at bus 6 is 1000 kVAr.

The load flow is run now again with the following buses having capacitor compensation:

a. Bus 5: 1500 kVAr
b. Bus 4: 1500 kVAr
c. Bus 8: 1200 kVAr
d. Bus 6: 1000 kVAr

Case 3

Here the impact of capacitor compensation at buses {5,4, 8 and 6} is found. In case 3, capacitor is placed at the following buses:

a. Bus 5: 1500 kVAr
b. Bus 4: 1500 kVAr
c. Bus 8: 1200 kVAr
d. Bus 6: 1000 kVAr

From the simulation result, the bus data, load data and line data are collected and shown in the following tables.

Table 4.10: Bus voltages and bus loads for Case 3

Bus ID	V sol [kV]	Ang sol [deg]	P Gen [kW]	Q Gen [kVAr]	P Load [kW]	Q Load [kVAr]
0	23	0	13040.2	-69.94	0	0
1	22.93	-0.6	0	0	1840	460
2	22.94	-1.3	0	0	980	340
3	22.68	-2.8	0	0	1790	446
4	22.47	-3.5	0	0	1598	1840
5	22.08	-5.2	0	0	1610	600
6	21.94	-5.8	0	0	780	110
7	21.62	-6.5	0	0	1150	60
8	21.13	-7.8	0	0	980	130
9	20.7	-8.3	0	0	1640	200

Table 4.11: Line flows, line losses, and line loading (%) for Case 3

Line ID	Bus From	Bus To	P [kW]	Q [kVAR]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L0	0	1	13040.21	-69.92	13040.4	100	327.3	39.64	54.6
L1	1	2	11171.95	-621.89	11189.24	99.8	281.7	3.33	47
L2	2	3	10169.5	-1103.07	10229.15	99.4	257.4	148.33	42.9
L3	3	4	8254.73	-1707.94	8429.56	97.9	214.6	96.49	35.8
L4	4	5	6469.81	-2163.92	6822.1	94.8	175.3	182.75	29.2
L5	5	6	4653.81	-1465.2	4879.02	95.4	127.6	44.21	21.3
L6	6	7	3834.62	-636.42	3887.07	98.7	102.3	64.5	17
L7	7	8	2613.38	-702.4	2706.12	96.6	72.3	75.12	12
L8	8	9	1588.16	189.93	1599.47	99.3	43.7	30.62	7.3
	Total loss							**685**	

The loss sensitivity factor of each bus of IEEE 9 bus system is determined and normalized voltage is calculated. The following table shows the LSI and normalized voltage value:

Table 4.12: Loss sensitivity factors for Case 3

Order	LSI	Start bus	End bus	Vi, p.u	Vj, p.u	Vnorm, p.u	Compensation required at bus no.
1	0.004783977	8	9	0.919	0.9	0.947368	9
2	-3.19554E-05	1	2	0.997	0.998	1.050526	--
3	-0.000046616	0	1	1	0.997	1.049474	--
4	-0.003116168	2	3	0.998	0.986	1.037895	--
5	-0.004617157	3	4	0.986	0.977	1.028421	--
6	-0.005122516	6	7	0.954	0.94	0.989474	7
7	-0.005570768	5	6	0.96	0.954	1.004211	6
8	-0.01436258	7	8	0.94	0.919	0.967368	8
9	-0.017280342	4	5	0.977	0.96	1.010526	--

From simulation data we see that total loss is 685 kW and all buses have minimum voltage of 20.7 kV or 0.9 p.u.

From the result we get a new set of buses {9, 7, 6 & 8} that requires further compensation. However, since our objective has been achieved i.e. obtaining minimum bus voltage at each bus and cost for additional placement of capacitor is more than the cost of energy saved from this addition capacitor placement, so we stop at this point.

It is to be noted here that additional capacitor placement increases the voltages at all buses but loss also increases.

It is found that if 750 kVAr is added at bus 6, net loss is 680 kW and if 900 kVAr is added, then total loss is 683 kW but voltage at bus does not reach minimum 90% of rated voltage i.e 20.7 kV. So 1000 kVAr is added at bus 6 and further addition of capacitor increases the voltage but loss also increases.

The net savings is found positive at this point. The calculation for net savings is shown below:

Cost Analysis &Verification of the worthiness of investment

A cost function that includes both the cost of investment and savings through loss reduction is used to determine size of the capacitor bank and ceiling of investment. The useful life of capacitor bank is assumed to be 5 years. Search for locations for installation of capacitors will be continued until no further los reduction is possible keeping cost function positive.

Eqn. 3.6 to 3.9 and corresponding notations of chapter 3 are referred. These Eqns. are used for verification of the worthiness of investment. Table 4.2 presents the assumptions considered for cost calculation

Before Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 783.65 KW

Total cost of energy loss, E1: BDT 21,28,07,994.00

After Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 685 KW

Total cost of energy loss, E2: BDT 18,60,18,600.00

Net cost of energy saved, E= BDT 2,67,89,394.00

Calculation for Cost of Investment

kVAr added in the system: 5200 kVAr

No. of locations: 4

Total Capacitor purchase cost, C_{cost}: BDT 2, 60, 00,000.00

Total Installation cost, I_{Cost}: BDT 1, 20,000.00

Total Operation and maintenance cost, OM_{Cost}: BDT 2, 00,000.00

Total cost of investment, I: BDT 2,63,20,000.00

Difference between cost of energy saved and total cost of investment: BDT 4,69,394.00

The difference is positive, so investment up to this amount of kVAr (5200 kVAr) is acceptable.

So, for summer peak loading condition of IEEE 9 bus distribution network, total optimum location for placement of capacitor is 4 and the buses are {5,4,8 & 6}.Total amount of capacitor installed is 5200 kVAr. The optimum sizes of capacitors are as follows:

a. Bus 5: 1500 kVAr
b. Bus 4: 1500 kVAr
c. Bus 8: 1200 kVAr
d. Bus 6: 1000 kVAr

4.2.2 Winter off peak loading condition

Case 4

After necessary parameters are inserted in to database of the PSAF and completion of drawing of IEEE 9 bus distribution network, the base case load flow is run without adding any capacitor to the network.

The winter off peak load is assumed to be 60% of summer peak load. From the simulation result, the bus data, load data, line data and LSF are collected/calculated and shown in the following tables:

Table 4.13: Bus Voltages for Case 4

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
0	23	23	0	20.7	25.3	7679.71	2869.04
1	23	22.91	-0.3	20.7	25.3	0	0
2	23	22.84	-0.7	20.7	25.3	0	0
3	23	22.52	-1.3	20.7	25.3	0	0
4	23	22.31	-1.5	20.7	25.3	0	0
5	23	21.91	-2.1	20.7	25.3	0	0
6	23	21.78	-2.4	20.7	25.3	0	0
7	23	21.55	-2.6	20.7	25.3	0	0
8	23	21.17	-3.1	20.7	25.3	0	0
9	23	20.9	-3.4	20.7	25.3	0	0

Table 4.14: Bus Loads for Case 4

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L1	1	1104	276	1137.98	97
L2	2	588	204	622.38	94.5
L3	3	1074	267.6	1106.84	97
L4	4	958.8	1104	1462.23	65.6
L5	5	966	360	1030.9	93.7
L6	6	468	66	472.63	99
L7	7	690	36	690.94	99.9
L8	8	588	78	593.15	99.1
L9	9	984	120	991.29	99.3

Table: 4.15Line flows, line losses, and line loading (%) for Case 4

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L0	0	1	7679.71	2869.02	8198.12	93.7	205.8	15.67	34.3
L1	1	2	6553.99	2522.72	7022.74	93.3	177	1.32	29.5
L2	2	3	5997.28	2311.28	6427.23	93.3	162.5	59.12	27.1
L3	3	4	4927.45	1974.5	5308.34	92.8	136.1	38.81	22.7
L4	4	5	3870.9	779.97	3948.7	98	102.2	62.1	17
L5	5	6	2811.18	339.28	2831.58	99.3	74.6	15.12	12.4
L6	6	7	2324.31	260.05	2338.81	99.4	62	23.69	10.3
L7	7	8	1603.83	208.95	1617.39	99.2	43.3	27.02	7.2
L8	8	9	979.32	114.92	986.04	99.3	26.9	11.6	4.5
	Total loss							**254.45**	

Table 4.16: Loss sensitivity factors arranged in descending order for Case 4

Order	LSI	Start bus	End bus	V_i (p.u)	V_j (p.u(	V_{norm} (p.u)	Compensation required at bus no.
1	0.006581405	2	3	0.993	0.979	1.0305263	--
2	0.006374782	4	5	0.97	0.953	1.003158	5
3	0.005509906	3	4	0.979	0.97	1.021053	--
4	0.004129913	7	8	0.937	0.92	0.968421	8
5	0.002599262	6	7	0.947	0.937	0.986316	7
6	0.002386791	8	9	0.92	0.909	0.956842	9
7	0.001351864	0	1	1	0.996	1.048421	--
8	0.001130581	5	6	0.953	0.947	0.996842	6
9	0.000133415	1	2	0.996	0.993	1.045263	--

So, it is found that the following buses need capacitor compensation in the following sequence: {5, 8, 7, 9,6}. The first three most responsive buses {5, 8 and 7} are initially selected for placement of capacitor.

From the load flow data, it is found that total reactive power generated under no compensation scenario is approx. 2870 kVAr. Moreover, it is found that all the buses are having the minimum voltage requirement. Total loss is 254.45 kW. So, here objective is to place capacitor at buses {5, 8 and 7} to reduce the losses further from 254.45 kW. However, it is also ensured that the cost function remains positive that is net saving prevails the overall investment required.

Case-5 (a)

Initially, 250 kVAr are added all buses and the impact is observed. The loss is found to be decreasing. After several combinations are tried, it is found that the following combination gives the maximum loss reduction:

a. Bus 5: 750 kVAr
b. Bus 8: 500 kVAr
c. Bus 7: 500 kVAr

The simulation result when capacitor compensation are made at Bus 5, 8 & 7 with above value are shown below:

Table 4.17: Bus voltages for Case 5(a)

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
0	23	23.00	0.0	20.7	25.3	7651.90	1121.27
1	23	22.94	-0.3	20.7	25.3	0	0
2	23	22.91	-0.8	20.7	25.3	0	0
3	23	22.69	-1.5	20.7	25.3	0	0
4	23	22.54	-1.8	20.7	25.3	0	0
5	23	22.27	-2.8	20.7	25.3	0	0
6	23	22.18	-3.1	20.7	25.3	0	0
7	23	22.01	-3.6	20.7	25.3	0	0
8	23	21.69	-4.2	20.7	25.3	0	0
9	23	21.44	-4.5	20.7	25.3	0	0

Table 4.18: Bus loads for Case 5(a) of IEEE 9 bus network

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L1	1	1104	276	1137.98	97
L2	2	588	204	622.38	94.5
L3	3	1074	267.6	1106.84	97
L4	4	958.8	1104	1462.23	65.6
L5	5	966	360	1030.9	93.7
L6	6	468	66	472.63	99
L7	7	690	36	690.94	99.9
L8	8	588	78	593.15	99.1
L9	9	984	120	991.29	99.3

Table: 4.19 Line flows, line losses, and line loading (%) for Case 5(a)

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L0	0	1	7651.91	1121.27	7733.62	98.9	194.1	13.94	32.4
L1	1	2	6476.12	801.19	6525.49	99.2	164.2	1.13	27.4
L2	2	3	5981.52	553.07	6007.03	99.6	151.4	51.29	25.2
L3	3	4	4895.55	207.82	4899.96	99.9	124.7	32.56	20.8
L4	4	5	3818.29	-904.73	3924.02	97.3	100.5	60.11	16.8
L5	5	6	2758.03	-591.21	2820.69	97.8	73.1	14.52	12.2
L6	6	7	2285.77	-656.83	2378.27	96.1	61.9	23.62	10.3
L7	7	8	1572.11	-233.73	1589.39	98.9	41.7	25.00	6.9
L8	8	9	961.40	128.29	969.92	99.1	25.8	10.69	4.3
	Total loss							**232.85**	

The above combination gives a loss of 232.85 kW. That is the loss is reduced by nearly 22 kW. If any additional capacitor is added at these buses, it is found that loss increases though voltage increases. But our objective is to reduce the losses not to increase bus voltages under these circumstances as all the buses have minimum required voltage. But for this amount of kVAr (1750 kVAr), cost function is negative. After searching for several combinations, it is found that for following combination of capacitor set, cost function is positive:

a. Bus 5: 300 kVAr
b. Bus 8: 250 kVAr
c. Bus 7: 300 kVAr

The simulation result when capacitor compensation are made at Bus 5, 8 & 7 with above value are shown below:

Table 4.20: Bus voltages for Case 5(b)

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
0	23	23.00	0.0	20.7	25.3	7661.98	2042.23
1	23	22.92	-0.3	20.7	25.3	0	0
2	23	22.87	-0.7	20.7	25.3	0	0
3	23	22.60	-1.4	20.7	25.3	0	0
4	23	22.42	-1.7	20.7	25.3	0	0
5	23	22.08	-2.4	20.7	25.3	0	0
6	23	21.97	-2.7	20.7	25.3	0	0
7	23	21.77	-3.1	20.7	25.3	0	0
8	23	21.42	-3.6	20.7	25.3	0	0
9	23	21.16	-3.9	20.7	25.3	0	0

Table 4.21: Bus loads for Case 5(b)

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L1	1	1104	276	1137.98	97
L2	2	588	204	622.38	94.5
L3	3	1074	267.6	1106.84	97
L4	4	958.8	1104	1462.23	65.6
L5	5	966	360	1030.9	93.7
L6	6	468	66	472.63	99
L7	7	690	36	690.94	99.9
L8	8	588	78	593.15	99.1
L9	9	984	120	991.29	99.3

Table: 4.22 Line flows, line losses, and line loading (%) for Case 5(b)

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L0	0	1	7661.98	2042.24	7929.48	96.6	199.0	14.66	33.2
L1	1	2	6539.46	1706.90	6758.55	96.8	170.2	1.22	28.4
L2	2	3	5975.21	1491.53	6158.55	97.0	155.4	54.10	25.9
L3	3	4	4902.37	1164.83	5038.86	97.3	128.7	34.72	21.5
L4	4	5	3850.85	-14.23	3850.88	100.0	99.2	58.51	16.5
L5	5	6	2796.91	-164.44	2801.74	99.8	73.3	14.57	12.2

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L6	6	7	2313.16	-234.74	2325.04	99.5	61.1	23.01	10.2
L7	7	8	1593.18	-11.97	1593.22	100.0	42.3	25.68	7.0
L8	8	9	973.72	114.91	980.48	99.3	26.4	11.20	4.4
Total loss								**237.6**	

The loss under this condition is 237.6 kW. It is found that the cost function is positive for above value. So, we stop here searching for optimum capacitor sizing. Now the cost function is verified to find the worthiness for this amount (850 kVAr) of investment.

Cost analysis &Verification of the worthiness of investment

Eqn. 3.6 to 3.9 and corresponding notations of chapter 3 are referred. These Eqns. are used for verification of the worthiness of investment for installation of 850 kVAr capacitors at following buses is verified:

a. Bus 5: 300 kVAr
b. Bus 8: 250 kVAr
c. Bus 7: 300 kVAr

Table 4.2 presents the assumptions considered for cost calculation

Before Compensation Cost of Energy Loss Calculation

Total cost of energy loss,E1= BDT 6,90,98,442.00

After Compensation Cost of Energy Loss Calculation

Total cost of energy loss, E2= BDT 6,45,22,656.00

Net cost of energy saved, E= BDT 45,75,786.00

Calculation for Cost of Investment

kVAr added in the system: 850 kVAr

No. of locations: 3

Total Capacitor purchase cost, C_{cost} = BDT 42,50,000.00

Total Installation cost, I_{Cost} = BDT 90,000.00

Total Operation and maintenance cost, OM_{Cost}= BDT 1,50,000.00

Total cost of investment, I= BDT 44,90,000.00

Difference between cost of energy saved and total cost of investment = BDT 85,786.00

The difference is positive, so investment up to this amount of kVAr (850 kVAr) is acceptable. However, it is found that if further capacitor is added, the loss is also reduced gradually. But for any additional investment beyond 850 kVAr, difference between cost of energy saved and total cost of investment becomes negative.

Case 5 (c): New case for summer peak condition

Keeping value of capacitors at buses 5, 8 and 7 in accordance with winter off peak condition, we now calculate new LSI for summer peak condition until we get the maximum combination for which loss is minimum. It is found that for the following combination, loss reduction is maximum.

a. Bus 5: 1500 kVAr
b. Bus 4: 1500 kVAr
c. Bus 6: 750 kVAr
d. Bus 7: 200 kVAr
e. Bus 8: 1200 kVAr

Under these conditions, loss becomes 684.44 kW. If further capacitor is added beyond these values, loss is increased. After calculating new LSI it is found that no bus needs compensation as all buses reached minimum 90% of rated voltage.

Cost analysis & Verification of the worthiness of investment

Eqn. 3.6 to 3.9 and corresponding notations of chapter 3 are referred. Using these Eqns. the worthiness of investment for installation of 5150 kVAr capacitors at following buses is verified:

a. Bus 5: 1500 kVAr
b. Bus 4: 1500 kVAr
c. Bus 6: 750 kVAr
d. Bus 7: 200 kVAr
e. Bus 8: 1200 kVAr

Before Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 783.65 kW, Total cost of energy loss, E1= BDT 21,28,07,994.00

After Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 684.44 kW, Total cost of energy loss, E2: BDT 18,58,66,56.00

Net cost of energy saved, E:BDT 2,69,41,468.00

Calculation for Cost of Investment

kVAr added in the system: 5150 kVAr, No. of locations: 5

Total Capacitor purchase cost, C_{cost}: BDT 2,57,50,000.00, Total Installation cost, Icost: BDT 1,50,000.00, Total Operation and maintenance cost, OMcost: BDT 5,00,000.00

Total cost of investment, I= BDT 2,64,00,000.00

Difference between cost of energy saved and total cost of investment= BDT 5,41,468.00

The difference is positive, so investment up to this amount of kVAr (5150kVAr) is acceptable. So, we stop here.

4.3 Simulation Result for IEEE 15 Bus Network

4.3.1 Summer peak loading condition

The base case load flow study network is shown in Figure 4.3.

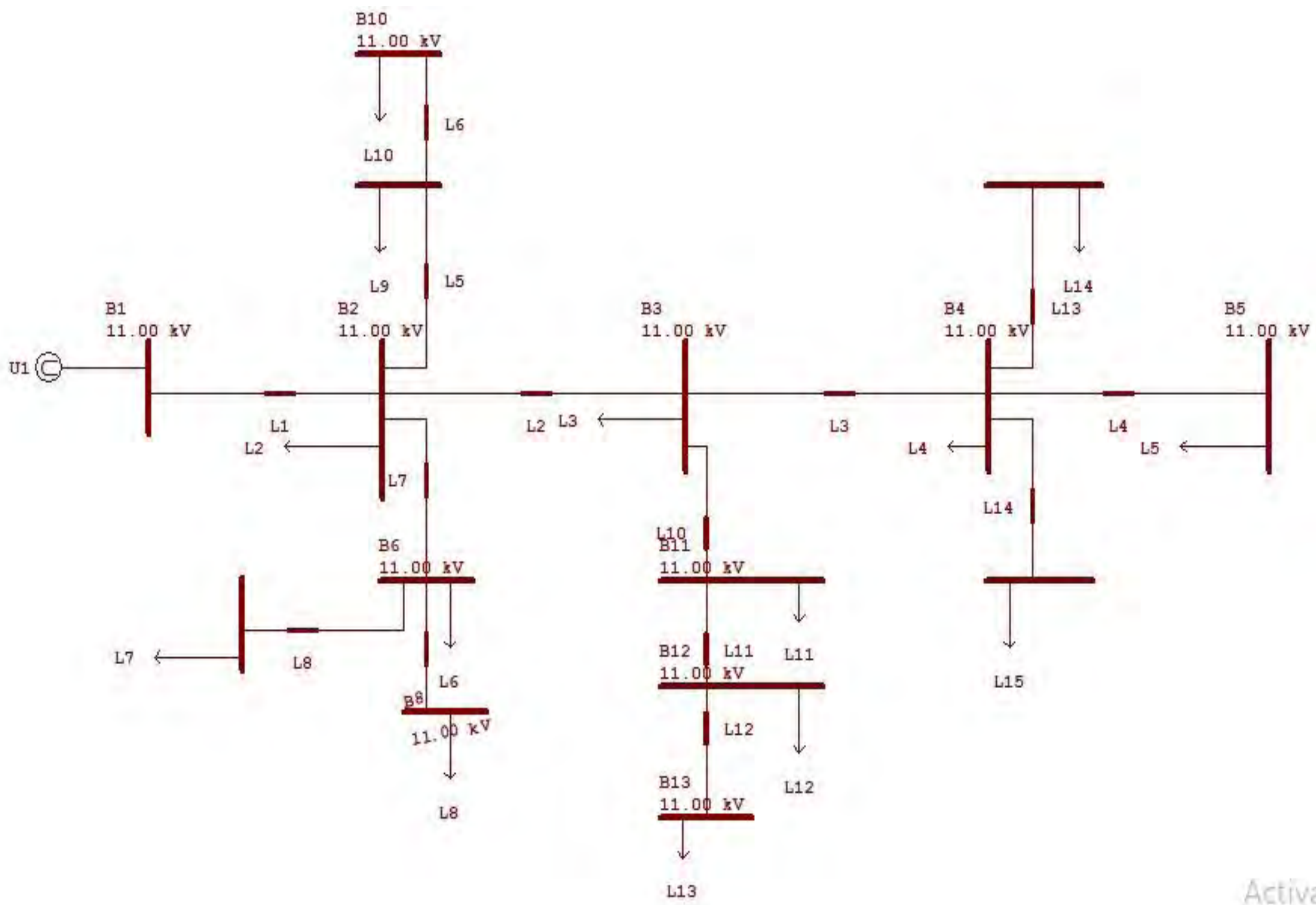


Fig: 4.3 IEEE 15 bus distribution network

Case 6

After necessary parameters are inserted in to database of the PSAF and completion of drawing of IEEE 15 bus distribution network, the base case load flow is run without adding any capacitor to the network. From the simulation result, the bus voltage, loads, and line flows are collected and presented in Tables 4.23 to 4.25.

Table 4.23: Bus voltages for Case 6

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
B1	11	11	0	9.9	12.1	1287.65	1301.09
B10	11	10.64	0.1	9.9	12.1	0	0
B11	11	10.45	0.1	9.9	12.1	0	0
B12	11	10.41	0.2	9.9	12.1	0	0
B13	11	10.39	0.2	9.9	12.1	0	0
B14	11	10.44	0.1	9.9	12.1	0	0
B15	11	10.43	0.1	9.9	12.1	0	0
B2	11	10.69	0	9.9	12.1	0	0
B3	11	10.52	0	9.9	12.1	0	0
B4	11	10.46	0	9.9	12.1	0	0
B5	11	10.45	0.1	9.9	12.1	0	0
B6	11	10.54	0.2	9.9	12.1	0	0
B7	11	10.52	0.2	9.9	12.1	0	0
B8	11	10.53	0.2	9.9	12.1	0	0
B9	11	10.65	0.1	9.9	12.1	0	0

Table 4.24Bus loads for Case 6

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L10	B10	44.1	44.99	63	70
L11	B11	140	143	200.12	70
L12	B12	70	71.41	100	70
L13	B13	44.1	44.99	63	70
L14	B14	70	71.41	100	70
L15	B15	140	143	200.12	70
L2	B2	44.1	44.99	63	70
L3	B3	70	71.41	100	70
L4	B4	140	142.83	200	70
L5	B5	44.1	44.99	63	70

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L6	B6	140	143	200.12	70
L7	B7	140	142.83	200	70
L8	B8	70	71.41	100	70
L9	B9	70	71.41	100	70

Table: 4.25Line flows, line losses, and line loading (%) for Case 6

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L10	B11	B3	-254.75	-258.76	363.12	-70.2	20.1	2.17	3.3
L11	B11	B12	114.76	115.79	163.02	70.4	9	0.6	1.5
L12	B12	B13	44.17	44.51	62.71	70.4	3.5	0.07	0.6
L13	B14	B4	-70	-71.4	99.98	-70	5.5	0.2	0.9
L14	B15	B4	-139.99	-142.97	200.1	-70	11.1	0.44	1.8
L1	B1	B2	1287.65	1301.09	1830.54	70.3	96.1	37.42	16
L2	B2	B3	735.3	744.5	1046.4	70.3	56.5	11.23	9.4
L3	B3	B4	397.18	402.93	565.78	70.2	31	2.43	5.2
L4	B4	B5	44.15	44.5	62.69	70.4	3.5	0.06	0.6
L5	B9	B2	-114.15	-115.89	162.67	-70.2	8.8	0.47	1.5
L6	B10	B9	-44.1	-44.99	63	-70	3.4	0.06	0.6
L7	B6	B2	-350.48	-356.48	499.92	-70.1	27.4	5.75	4.6
L8	B7	B6	-139.99	-142.81	199.98	-70	11	0.39	1.8
L9	B6	B8	70.11	70.94	99.74	70.3	5.5	0.11	0.9
	Total loss							**61.4**	

Sensitivity Analysis

The loss sensitivity factor of each bus of IEEE 15 bus system is determined by using Eqn. (4.1). LSF gives the sequence for placement of capacitor. Then normalized voltage is calculated. The normalized voltage value tells which bus needs capacitor compensation. The following table shows the LSF and normalized voltage value:

Table 4.26 Loss sensitivity factors arranged in descending order for Case 6

Order	LSI	Start bus	End bus	V_i (p.u)	V_j (p.u)	V_{norm} (p.u)	Compensation required at bus no.
1	0.029028	B1	B2	1	0.971	1.0221053	--
2	0.017933	B2	B6	0.971	0.958	1.008421	6
3	0.014361	B2	B3	0.971	0.957	1.007368	3

Order	LSI	Start bus	End bus	V_i (p.u)	V_j (p.u)	V_{norm} (p.u)	Compensation required at bus no.
4	0.009722	B3	B11	0.957	0.95	1	11
5	0.006072	B3	B4	0.957	0.951	1.001053	4
6	0.004484	B11	B12	0.95	0.946	0.995789	12
7	0.004077	B4	B14	0.951	0.949	0.998947	14
8	0.003529	B2	B9	0.971	0.968	1.018947	--
9	0.002254	B6	B8	0.958	0.957	1.007368	8
10	0.002188	B4	B15	0.951	0.949	0.998947	15
11	0.00196	B6	B7	0.958	0.956	1.006316	7
12	0	B12	B13	0.946	0.945	0.994737	13
13	0	B4	B5	0.951	0.95	1	5
14	0		B9	B10	0.968	1.018947	--

So, it is found that the following buses need capacitor compensation in the following sequence: {6,3,11,4,12,14,8,15,7,13,5}. The first three most responsive buses {6,3and 11} are initially selected for placement of capacitor.

From the load flow data, it is found that total reactive power demanded under no compensation scenario is approx. 1300 kVAr. Moreover, all the buses of IEEE 15 bus distribution network are having the minimum voltage requirement. Total loss is 61.4 kW. So, here objective is to place capacitor at buses {6, 3 and 11} toreduce the losses further from 61.4 kW. However, it is also ensured that the cost function remains positive that is net saving prevail the overall investment required.

Initially, 250 kVAr are added all buses and the impact is observed. The loss is found to be decreasing. After several combinations are tried, it is found that the following combination gives the maximum loss reduction and if further capacitor is added beyond these values, loss is increased:

a. Bus 6: 500 kVAr
b. Bus 3: 500 kVAr
c. Bus 11: 300 kVAr

The above combination gives a loss of 31.6 kW. That is the loss is reduced by nearly 30 kW.

Case 7

Here the impact of capacitor compensation at buses {6,3 and 11} is found. In case 2, capacitor is placed at the following buses:

a. Bus 6: 500 kVAr
b. Bus 3: 500 kVAr
c. Bus 11: 300 kVAr

From the simulation result, the bus voltage, loads, and line flows are collected and presented in Tables 4.27 to 4.30:

Table 4.27Bus voltages for Case 7

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
B1	11	11	0	9.9	12.1	1258.01	28.37
B10	11	10.8	-0.7	9.9	12.1	0	0
B11	11	10.73	-1.4	9.9	12.1	0	0
B12	11	10.68	-1.3	9.9	12.1	0	0
B13	11	10.67	-1.3	9.9	12.1	0	0
B14	11	10.68	-1.2	9.9	12.1	0	0
B15	11	10.68	-1.2	9.9	12.1	0	0
B2	11	10.84	-0.8	9.9	12.1	0	0
B3	11	10.77	-1.2	9.9	12.1	0	0
B4	11	10.71	-1.2	9.9	12.1	0	0
B5	11	10.7	-1.2	9.9	12.1	0	0
B6	11	10.78	-1.2	9.9	12.1	0	0
B7	11	10.76	-1.2	9.9	12.1	0	0
B8	11	10.77	-1.2	9.9	12.1	0	0
B9	11	10.81	-0.7	9.9	12.1	0	0

Table 4.28 Bus loads for Case 7

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L10	B10	44.1	44.99	63	70
L11	B11	140	143	200.12	70
L12	B12	70	71.41	100	70
L13	B13	44.1	44.99	63	70

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L14	B14	70	71.41	100	70
L15	B15	140	143	200.12	70
L2	B2	44.1	44.99	63	70
L3	B3	70	71.41	100	70
L4	B4	140	142.83	200	70
L5	B5	44.1	44.99	63	70
L6	B6	140	143	200.12	70
L7	B7	140	142.83	200	70
L8	B8	70	71.41	100	70
L9	B9	70	71.41	100	70

Table: 4.29Line flows, line losses, and line loading (%) for Case 7

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L10	B3	B11	255.75	-26.46	257.11	99.5	13.8	1.02	3.4
L11	B11	B12	114.73	115.73	162.97	70.4	8.8	0.57	2.2
L12	B12	B13	44.17	44.49	62.69	70.5	3.4	0.07	0.8
L13	B4	B14	70.19	70.99	99.83	70.3	5.4	0.19	1.3
L14	B4	B15	140.42	142.73	200.22	70.1	10.8	0.42	2.7
L1	B1	B2	1258.01	28.37	1258.33	100	66	17.68	16.5
L2	B2	B3	728.1	-26.78	728.59	99.9	38.8	5.28	9.7
L3	B3	B4	397.08	402.75	565.58	70.2	30.3	2.32	7.6
L4	B4	B5	44.15	44.48	62.67	70.5	3.4	0.05	0.8
L5	B2	B9	114.61	115.63	162.8	70.4	8.7	0.45	2.2
L6	B9	B10	44.16	44.47	62.67	70.5	3.3	0.06	0.8
L7	B2	B6	353.51	-122.19	374.03	94.5	19.9	3.04	5
L8	B6	B7	140.38	142.53	200.05	70.2	10.7	0.38	2.7
L9	B6	B8	70.11	70.93	99.73	70.3	5.3	0.11	1.3

Table 4.30 Loss sensitivity factors arranged in descending order for Case 7

Order	LSI	Start bus	End bus	Vi (p.u)	Vj (p.u)	Vnorm (p.u)	Compensation required at bus no.
1	0.005802	B3	B4	0.979	0.973	1.0242105	--
2	0.004257	B11	B12	0.975	0.971	1.022105	--
3	0.003895	B4	B14	0.973	0.971	1.022105	--
4	0.003423	B2	B9	0.986	0.982	1.033684	--
5	0.002154	B6	B8	0.98	0.979	1.030526	--
6	0.00209	B4	B15	0.973	0.971	1.022105	--

Order	LSI	Start bus	End bus	Vi (p.u)	Vj (p.u)	Vnorm (p.u)	Compensation required at bus no.
7	0.001873	B6	B7	0.98	0.978	1.029474	--
8	0	B2	B3	0.986	0.979	1.030526	--
9	0	B12	B13	0.971	0.97	1.021053	--
10	0	B9	B10	0.982	0.981	1.032632	--
11	0	B3	B11	0.979	0.975	1.026316	--
12	0	B1	B2	1	0.986	1.037895	--
13	0	B4	B5	0.973	0.972	1.023158	--
14	-0.00435	B2	B6	0.986	0.98	1.031579	--

From the new LSI and V_{norm} as shown in Table 4.22, it is found that none of the bus need any compensation and no candidate bus is found.

So, the combination that gives maximum loss reduction is as follows and if further capacitor is added beyond these values, loss is increased:

a. Bus 6: 500 kVAr
b. Bus 3: 500 kVAr
c. Bus 11: 300 kVAr

Cost analysis & Verification of the worthiness of investment

Eqn. 3.6 to 3.9 and corresponding notations of chapter 3 are referred. Using these Eqns. the worthiness of investment for installation of 1300 kVAr capacitors at following buses is verified:

a. Bus 6: 500 kVAr
b. Bus 3: 500 kVAr
c. Bus 11: 300 kVAr

Before Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 61.4 kW

Total cost of energy loss, E1= BDT 1,66,73,784.00

After Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 31.6 kW

Total cost of energy loss, E2: BDT 85,81,296.00

Net cost of energy saved, E:BDT 80,92,488.00

Calculation for Cost of Investment

kVAr added in the system: 1300 kVAr

No. of locations: 3

Total Capacitor purchase cost, C_{cost}: BDT 65,00,000.00

Total Installation cost, I_{cost}: BDT 90,000.00

Total Operation and maintenance cost, OM_{cost}: BDT 1,50,000.00

Total cost of investment, I= BDT 67,40,000.00

Difference between cost of energy saved and total cost of investment= BDT 13,52,488.00

The difference is positive, so investment up to this amount of kVAr (1300kVAr) is acceptable. However, it is found that if further capacitor is added to next responsive bus at 4, the loss is also reduced gradually. Total power loss: 31.4 kW when 200 kVAr is added to the system at next responsive bus i.eat bus 4. But to decrease 0.2 kW loss, we need to add additional 200 kVAr, the savings will be BDT 54,312 but the investment cost for this is 10,80,000.00, which is not justified. So, we stop here.

4.3.2 Winter off peak loading condition

Case8

After necessary parameters are inserted in to database of the PSAF and completion of drawing of IEEE 15 bus distribution network, the base case load flow is run without adding any capacitor to the network. The winter off peak load is assumed to be 80% of summer peak load. From the simulation result, the bus voltage, loads, and line flows are collected and presented in Tables 4.31 to 4.34

Table 4.31Bus voltages for Case 8

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
B1	11	11	0	9.9	12.1	1019.51	1029.4
B10	11	10.71	0.1	9.9	12.1	0	0
B11	11	10.57	0.1	9.9	12.1	0	0
B12	11	10.53	0.1	9.9	12.1	0	0
B13	11	10.52	0.1	9.9	12.1	0	0
B14	11	10.55	0.1	9.9	12.1	0	0
B15	11	10.55	0.1	9.9	12.1	0	0
B2	11	10.75	0	9.9	12.1	0	0
B3	11	10.62	0	9.9	12.1	0	0
B4	11	10.57	0	9.9	12.1	0	0
B5	11	10.57	0	9.9	12.1	0	0
B6	11	10.64	0.1	9.9	12.1	0	0
B7	11	10.62	0.2	9.9	12.1	0	0
B8	11	10.63	0.2	9.9	12.1	0	0
B9	11	10.72	0.1	9.9	12.1	0	0

Table 4.32Bus loads for Case 8

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L10	B11	112	114.4	160.1	70
L11	B12	56	57.13	80	70
L12	B13	35.28	35.99	50.4	70
L13	B14	56	57.13	80	70
L14	B15	112	114.4	160.1	70
L1	B2	35.28	35.99	50.4	70

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L2	B3	56	57.13	80	70
L3	B4	112	114.26	160	70
L4	B5	35.28	35.99	50.4	70
L5	B6	112	114.4	160.1	70
L6	B7	112	114.26	160	70
L7	B8	56	57.13	80	70
L8	B9	56	57.13	80	70
L9	B10	35.28	35.99	50.4	70

Table: 4.33Line flows, line losses, and line loading (%) for Case 8

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L10	B3	B11	205.04	207.1	291.43	70.4	15.8	1.35	2.6
L11	B11	B12	91.69	92.33	130.12	70.5	7.1	0.37	1.2
L12	B12	B13	35.32	35.49	50.07	70.5	2.7	0.05	0.5
L13	B4	B14	56.13	56.68	79.76	70.4	4.4	0.13	0.7
L14	B4	B15	112.27	114.04	160.03	70.2	8.7	0.27	1.5
L1	B1	B2	1019.51	1029.4	1448.81	70.4	76	23.44	12.7
L2	B2	B3	585.27	591.96	832.44	70.3	44.7	7.02	7.5
L3	B3	B4	317.22	321.41	451.59	70.2	24.5	1.52	4.1
L4	B4	B5	35.31	35.48	50.06	70.5	2.7	0.03	0.5
L5	B2	B9	91.61	92.24	130	70.5	7	0.3	1.2
L6	B9	B10	35.31	35.47	50.05	70.6	2.7	0.04	0.4
L7	B2	B6	283.92	286.8	403.56	70.4	21.7	3.61	3.6
L8	B6	B7	112.24	113.88	159.9	70.2	8.7	0.25	1.4
L9	B6	B8	56.07	56.63	79.69	70.4	4.3	0.07	0.7

Table 4.34 Loss sensitivity factors for Case 8

Order	LSI	Start bus	End bus	Vi, p.u	Vj, p.u	Vnorm, p.u	Compensation required at bus no.
1	0.022329	B1	B2	1	0.977	1.0284211	--
2	0.013285	B2	B6	0.977	0.967	1.0178947	--
3	0.012159	B2	B3	0.977	0.966	1.0168421	--
4	0.006361	B3	B11	0.966	0.961	1.0115789	--
5	0.00447	B3	B4	0.966	0.961	1.0115789	--
6	0.004382	B11	B12	0.961	0.957	1.0073684	12
7	0.003993	B4	B14	0.961	0.959	1.0094737	14
8	0.003486	B2	B9	0.977	0.975	1.0263158	--

Order	LSI	Start bus	End bus	Vi, p.u	Vj, p.u	Vnorm, p.u	Compensation required at bus no.
9	0.002212	B6	B8	0.967	0.966	1.0168421	--
10	0.002142	B4	B15	0.961	0.959	1.0094737	15
11	0.001924	B6	B7	0.967	0.965	1.0157895	--
12	0	B12	B13	0.957	0.956	1.0063158	13
13	0	B4	B5	0.961	0.961	1.0115789	--
14	0	B9	B10	0.975	0.974	1.0252632	--

So, it is found that the following buses need capacitor compensation in the following sequence: {12, 14, 15,13}. The most responsive three buses {12, 14, 15} are selected for placement of capacitor.

From the load flow data, it is found that total reactive power generated under no compensation scenario is approx. 1030 kVAr. Moreover, it is found that all the buses are having the minimum voltage requirement. Total loss is 38.4 kW. So, here objective is to place capacitor at buses {12, 14, 15} to reduce the losses further from 38.4 kW. However, it is also ensured that the cost function remains positive that is net saving prevails the overall investment required.

Initially, 100 kVAr are added all buses and the impact is observed. The loss is found to be decreasing. After several combinations are tried, it is found that the following combination gives the maximum loss reduction:

a. Bus 12: 250 kVAr
b. Bus 14: 250 kVAr
c. Bus 15: 250 kVAr

The above combination gives a loss of 23.2 kW. That is the loss is reduced by nearly 15 kW.

Case9

Here the impact of capacitor compensation at buses {12,14 and 15} is found. In case 2, capacitor is placed at the following buses

a. Bus 12: 250 kVAr
b. Bus 14: 250 kVAr
c. Bus 15: 250 kVAr

From the simulation result, LSF are calculated and shown in the following tables:

Table 4.35 Loss sensitivity factors arranged in descending order for Case 9

Order	LSI	Start bus	End bus	Vi, p.u	Vj, p.u	Vnorm, p.u	Compensation required at bus no.
1	0.013043	B2	B6	0.986	0.975	1.0263158	--
2	0.006699	B1	B2	1	0.986	1.0378947	--
3	0.003423	B2	B9	0.986	0.983	1.0347368	--
4	0.002176	B6	B8	0.975	0.974	1.0252632	--
5	0.001892	B6	B7	0.975	0.974	1.0252632	--
6	0	B3	B11	0.981	0.978	1.0294737	--
7	0	B12	B13	0.979	0.978	1.0294737	--
8	0	B4	B5	0.98	0.979	1.0305263	--
9	0	B9	B10	0.983	0.982	1.0336842	--
10	-0.00199	B2	B3	0.986	0.981	1.0326316	--
11	-0.00206	B4	B15	0.98	0.98	1.0315789	--
12	-0.00289	B3	B4	0.981	0.98	1.0315789	--
13	-0.00423	B11	B12	0.978	0.979	1.0305263	--
14	-0.00768	B4	B14	0.98	0.981	1.0326316	--

From the new LSF and V_{norm} as shown in table 4.27, it is found that none of the bus needs any compensation and no candidate bus is found.

So, the combination that gives maximum loss reduction is as follows and if further capacitor is added beyond these values, loss is increased:

a. Bus 12: 250 kVAr
b. Bus 14: 250 kVAr
c. Bus 15: 250 kVAr

Cost analysis &Verifying the worthiness of investment

Eqn. 3.6 to 3.9 and corresponding notations of chapter 3 are referred. Using these Eqns. worthiness of investment for installation of 750 kVAr capacitors at following buses is verified:

a. Bus 12: 250 kVAr
b. Bus 14: 250 kVAr
c. Bus 15: 250 kVAr

Before Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 38.4 kW, Total cost of energy loss, E1: BDT 1,04,27,904.00

After Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 23.2 kW, Total cost of energy loss, E2: BDT 63,00,192.00
Net cost of energy saved, E: BDT 41,27,712.00

Calculation for Cost of Investment

kVAr added in the system: 750 kVAr, No. of locations: 3

Total Capacitor purchase cost, C_{cost}: BDT 37,50,000.00,

Total Installation cost, I_{cost}: BDT 90,000.00, Total Operation and maintenance cost, OM_{cost}: BDT 1,50,000.00

Total cost of investment, I= BDT 39,90,000.00

Difference between cost of energy saved and total cost of investment:BDT 1,37,712.00

The difference is positive, so investment up to this amount of kVAr (750kVAr) is acceptable. If further capacitor is added beyond these values, loss is increased.

Case 9 (b): New case for summer peak condition

Keeping value of capacitors at buses 12, 14 and 15 in accordance with winter off peak condition, we now add capacitor at 6 and 3 for summer peak condition until we get the maximum combination for which loss is minimum. It is found that for the following combination, loss reduction is maximum.

f. Bus 6: 400 kVAr
g. Bus 3: 100 kVAr
h. Bus 12: 250 kVAr
i. Bus 14: 250 kVAr
j. Bus 15: 250 kVAr

Under these conditions, loss becomes 30.6 kW. If further capacitor is added beyond these values, loss is increased. And new LSI indicates that no bus needs compensation.

Order	LSI	Start bus	End bus	Vi (p.u)	Vj (p.u)	Vnorm (p.u)	Compensation required at bus no.
1	0.00929	B3	B4	0.979	0.975	1.036842	--
2	0.004257	B11	B12	0.975	0.974	1.029474	--
3	0	B4	B14	0.974	0.973	1.030526	--
4	0.003871	B2	B9	0.976	0.977	1.026316	--
5	0.002077	B6	B8	0.976	0.976	1.027368	--

Order	LSI	Start bus	End bus	Vi (p.u)	Vj (p.u)	Vnorm (p.u)	Compensation required at bus no.
6	0.029028	B4	B15	1	0.985	1.025263	--
7	0.015949	B6	B7	0.985	0.979	1.028421	--
8	0.005802	B2	B3	0.979	0.976	1.033684	--
9	0	B12	B13	0.976	0.976	1.028421	--
10	0.00343	B9	B10	0.985	0.982	1.027368	--
11	0	B3	B11	0.982	0.981	1.027368	--
12	0.017426	B1	B2	0.985	0.978	1.027368	--
13	0.001881	B4	B5	0.978	0.976	1.032632	--
14	0.002163	B2	B6	0.978	0.977	1.024211	--

Cost analysis & Verification of the worthiness of investment

Eqn. 3.6 to 3.9 and corresponding notations of chapter 3 are referred. Using these Eqns. the worthiness of investment for installation of 1250 kVAr capacitors at following buses is verified:

a. Bus 6: 400 kVAr
b. Bus 3: 100 kVAr
c. Bus 12: 250 kVAr
d. Bus 14: 250 kVAr
e. Bus 15: 250 kVAr

Before Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 61.4 kW, Total cost of energy loss, E1= BDT 1,66,73,784.00

After Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 30.6 kW, Total cost of energy loss, E2: BDT 83,09,736.00

Net cost of energy saved, E:BDT 83,64,048.00

Calculation for Cost of Investment
kVAr added in the system: 1250 kVAr, No. of locations: 5

Total Capacitor purchase cost, C_{cost}: BDT 62,50,000.00,

Total Installation cost, Icost: BDT 1,50,000.00, Total Operation and maintenance cost, OMcost: BDT 5,00,000.00

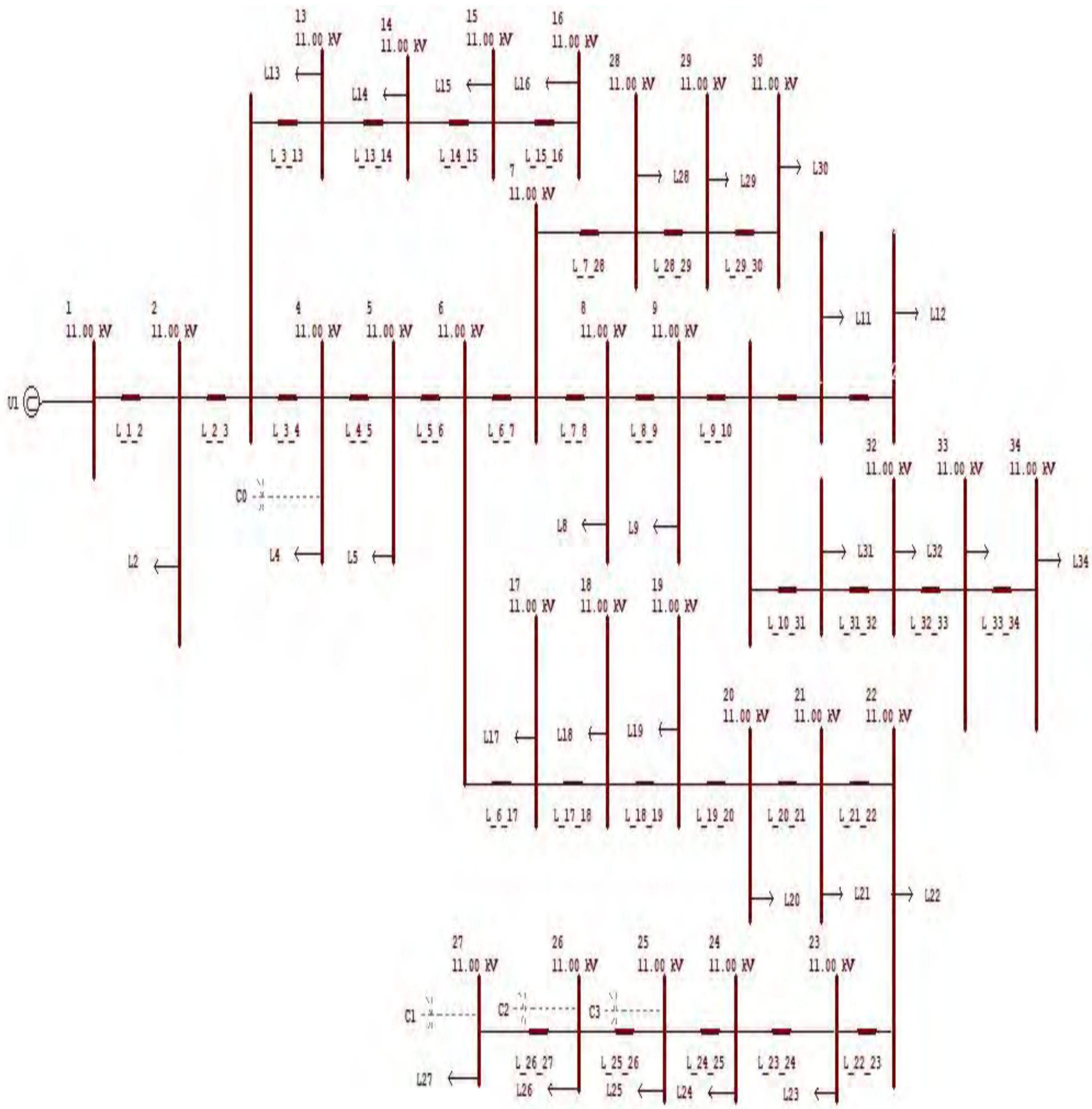
Total cost of investment, I= BDT 69,00,000.00
Difference between cost of energy saved and total cost of investment= BDT 14,64,048.00

The difference is positive, so investment up to this amount of kVAr (1250kVAr) is acceptable. So, we stop here.

4.4 Simulation Result for IEEE 34 Bus Network

4.4.1 Summer peak loading condition

The base case load flow study network is shown in Figure 4.4. At first, the IEEE 34 bus distribution network is drawn into the simulation software. Here, connection of the capacitor is shown by the dotted line. It means, under this circumstance, the capacitors are not connected to the network, it is deactivated. The Figure 4.4 is shown at next page



. Fig: 4.4 IEEE 34 bus distribution network

Case 10

After necessary parameters are inserted in to database of the PSAF and completion of drawing of IEEE 34 bus distribution network, the base case load flow is run without adding any capacitor to the network.

From the simulation result, the bus voltage, loads, line flows and calculation of Loss sensitivity factors (LSF) are collected and presented in Tables 4.36 to 4.39

Table 4.36BusVoltages for case 10 of IEEE 34 bus network

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
1	11	11	0	9.9	12.1	4857.39	2931.15
10	11	10.57	0.6	9.9	12.1	0	0
11	11	10.56	0.6	9.9	12.1	0	0
12	11	10.56	0.6	9.9	12.1	0	0
13	11	10.88	0.1	9.9	12.1	0	0
14	11	10.87	0.1	9.9	12.1	0	0
15	11	10.87	0.1	9.9	12.1	0	0
16	11	10.87	0.1	9.9	12.1	0	0
17	11	10.63	0.5	9.9	12.1	0	0
18	11	10.58	0.5	9.9	12.1	0	0
19	11	10.54	0.6	9.9	12.1	0	0
2	11	10.94	0.1	9.9	12.1	0	0
20	11	10.5	0.7	9.9	12.1	0	0
21	11	10.47	0.8	9.9	12.1	0	0
22	11	10.44	0.8	9.9	12.1	0	0
23	11	10.41	0.9	9.9	12.1	0	0
24	11	10.38	1	9.9	12.1	0	0
25	11	10.37	1	9.9	12.1	0	0
26	11	10.36	1	9.9	12.1	0	0
27	11	10.36	1	9.9	12.1	0	0
28	11	10.63	0.5	9.9	12.1	0	0
29	11	10.63	0.5	9.9	12.1	0	0
3	11	10.88	0.1	9.9	12.1	0	0
30	11	10.63	0.5	9.9	12.1	0	0
31	11	10.57	0.6	9.9	12.1	0	0
32	11	10.56	0.6	9.9	12.1	0	0
33	11	10.56	0.7	9.9	12.1	0	0

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
34	11	10.56	0.7	9.9	12.1	0	0
4	11	10.8	0.2	9.9	12.1	0	0
5	11	10.74	0.3	9.9	12.1	0	0
6	11	10.67	0.4	9.9	12.1	0	0
7	11	10.63	0.5	9.9	12.1	0	0
8	11	10.61	0.5	9.9	12.1	0	0
9	11	10.58	0.6	9.9	12.1	0	0

Table 4.37Bus Loads for case 10 of IEEE 34 bus network

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L30	30	75	48	89.04	84.2
L20	20	230	142.5	270.57	85
L31	31	57	34.5	66.63	85.6
L21	21	230	142.5	270.57	85
L11	11	230	142.5	270.57	85
L32	32	57	34.5	66.63	85.6
L22	22	230	142.5	270.57	85
L12	12	137	84	160.7	85.3
L33	33	57	34.5	66.63	85.6
L23	23	230	142.5	270.57	85
L13	13	72	45	84.91	84.8
L34	34	57	34.5	66.63	85.6
L24	24	230	142.5	270.57	85
L14	14	72	45	84.91	84.8
L25	25	230	142.5	270.57	85
L15	15	72	45	84.91	84.8
L26	26	230	142.5	270.57	85
L16	16	13.5	7.5	15.44	87.4
L27	27	137	85	161.23	85
L17	17	230	142.5	270.57	85
L28	28	75	48	89.04	84.2
L18	18	230	142.5	270.57	85
L29	29	75	48	89.04	84.2
L19	19	230	142.5	270.57	85
L2	2	230	142.5	270.57	85
L4	4	230	142.5	270.57	85
L5	5	230	142.5	270.57	85
L8	8	230	142.5	270.57	85
L9	9	230	142.5	270.57	85

Table: 4.38Line flows, line losses, and line loading (%) for Case 10

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L_15_16	15	16	13.54	7.45	15.46	87.6	0.8	0	0.1
L_25_26	25	26	367.2	227.19	431.8	85	24.1	0.23	4
L_26_27	26	27	136.96	84.85	161.11	85	9	0.03	1.5
L_8_9	8	9	828.96	506.18	971.28	85.3	52.9	2.64	8.8
L_13_14	13	14	157.56	97.11	185.08	85.1	9.8	0.06	1.6
L_23_24	23	24	830.85	512.19	976.04	85.1	54.1	2.77	9
L_33_34	33	34	57.04	34.39	66.61	85.6	3.6	0	0.6
L_7_8	7	8	1061.81	648.94	1244.41	85.3	67.6	2.87	11.3
L_14_15	14	15	85.55	52.34	100.29	85.3	5.3	0.01	0.9
L_24_25	24	25	598.14	369.59	703.11	85.1	39.1	0.96	6.5
L_7_28	7	28	225.15	143.52	267	84.3	14.5	0.1	2.4
L_11_12	11	12	137	83.88	160.64	85.3	8.8	0.02	1.5
L_21_22	21	22	1300.1	798.21	1525.58	85.2	84.1	5.56	14
L_31_32	31	32	171.11	103.02	199.73	85.7	10.9	0.07	1.8
L_22_23	22	23	1064.6	655.04	1249.98	85.2	69.2	3.76	11.5
L_32_33	32	33	114	68.72	133.11	85.6	7.3	0.02	1.2
L_10_11	10	11	367.25	226.26	431.35	85.1	23.6	0.22	3.9
L_20_21	20	21	1535.65	941.73	1801.41	85.2	99	5.56	16.5
L_19_20	19	20	1772.95	1085.63	2078.93	85.3	113.9	7.35	19
L_10_31	10	31	228.2	137.37	266.36	85.7	14.5	0.1	2.4
L_29_30	29	30	75.01	47.83	88.96	84.3	4.8	0.01	0.8
L_2_3	2	3	4596.25	2776.22	5369.63	85.6	283.5	25.86	47.2
L_3_13	3	13	229.67	141.96	270	85.1	14.3	0.1	2.4
L_1_2	1	2	4857.41	2931.15	5673.27	85.6	297.8	31.12	49.6
L_9_10	9	10	596.31	363.57	698.41	85.4	38.1	0.91	6.4
L_6_7	6	7	1293.28	793.24	1517.17	85.2	82.1	6.35	13.7
L_6_17	6	17	2496.79	1521.18	2923.69	85.4	158.1	13.46	26.4
L_5_6	5	6	3815.99	2321.44	4466.64	85.4	240.2	25.87	40
L_4_5	4	5	4075.01	2471.77	4766.06	85.5	254.7	29.1	42.5
L_17_18	17	18	2253.4	1375.26	2639.91	85.4	143.4	10.15	23.9
L_18_19	18	19	2013.24	1230.2	2359.35	85.3	128.7	10.33	21.4
L_28_29	28	29	150.07	95.67	177.97	84.3	9.7	0.04	1.6
L_3_4	3	4	4340.77	2623.92	5072.2	85.6	269.2	35.75	44.9

Table 4.39 Loss sensitivity factors arranged in descending order for Case 10

Order	LSI	Start bus	End bus	V_i (p.u)	V_j (p.u)	V_{norm} (p.u)	Compensation required at bus no.
1	0.013137	3	4	0.989	0.982	1.0336842	--
2	0.012812	4	5	0.982	0.976	1.0273684	--
3	0.011933	5	6	0.976	0.97	1.0210526	--
4	0.009347	1	2	1	0.994	1.0463158	--
5	0.009134	2	3	0.994	0.989	1.0410526	--
6	0.008102	18	19	0.962	0.958	1.0084211	19
7	0.007879	6	17	0.97	0.966	1.0168421	--
8	0.007645	21	22	0.952	0.949	0.9989474	22
9	0.007489	19	20	0.958	0.955	1.0052632	20
10	0.007415	17	18	0.966	0.962	1.0126316	--
11	0.007364	6	7	0.97	0.967	1.0178947	--
12	0.006732	22	23	0.949	0.946	0.9957895	23
13	0.006166	20	21	0.955	0.952	1.0021053	21
14	0.005557	7	8	0.967	0.965	1.0157895	--
15	0.004839	23	24	0.946	0.944	0.9936842	24
16	0.00465	8	9	0.965	0.962	1.0126316	--
17	0.003888	24	25	0.944	0.942	0.9915789	25
18	0.003744	9	10	0.962	0.961	1.0115789	--
19	0.001952	25	26	0.942	0.942	0.9915789	26
20	0.001876	10	11	0.961	0.96	1.0105263	--
21	0.000976	26	27	0.942	0.942	0.9915789	27
22	0.00094	32	33	0.96	0.96	1.0105263	--
23	0.00094	11	12	0.96	0.96	1.0105263	--
24	0.000938	31	32	0.961	0.96	1.0105263	--
25	0.000938	10	31	0.961	0.961	1.0115789	--
26	0.000928	28	29	0.966	0.966	1.0168421	--
27	0.000926	7	28	0.967	0.966	1.0168421	--
28	0.000887	14	15	0.988	0.988	1.04	--
29	0.000885	3	13	0.989	0.989	1.0410526	--
30	0.000885	13	14	0.989	0.988	1.04	--
31	0	29	30	0.966	0.966	1.0168421	--
32	0	33	34	0.96	0.96	1.0105263	--
33	0	15	16	0.988	0.988	1.04	--

So, it is found that the following buses need capacitor compensation in the following sequence: {19,22,20,23,21,24,25,26,27}. The first three most responsive buses {19,22 and 20} are initially selected for placement of capacitor.

From the load flow data, it is found that total reactive power generated under no compensation scenario is approx. 3000 kVAr. Moreover, all the buses are having the minimum voltage requirement. Total loss is 221.4 kW. So, here objective is to place capacitor at buses {19,22 and 20} to reduce the losses further from 221.4 kW. However, it is also ensured that the cost function remains positive that is net saving prevail over the overall investment required.

Several combination of capacitor are added to the system. It is found that under these circumstances, the following set of capacitor reduces the loss maximum:

a. Bus 19: 750 kVAr
b. Bus 22: 500 kVAr
c. Bus 20: 750 kVAr

After adding capacitors at these, the sensitivity is calculated again to see the impact of these

Case 11

Here the impact of capacitor compensation at buses {19,22 and 20} is found. In case 2, capacitor is placed at the following buses

a. Bus 19: 750 kVAr
b. Bus 22: 500 kVAr
c. Bus 20: 750 kVAr

From the simulation result, the bus voltage, loads, line flows and calculation of loss sensitivity factors (LSF) are collected and presented in Tables 4.40 to 4.42

Table 4.40 Bus voltages and loads for Case11

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]	P Load [kW]	Q Load [kVAr]
1	11	11	0	9.9	12.1	4806.07	1068.43	0	0
10	11	10.61	0	9.9	12.1	0	0	0	0
11	11	10.61	0	9.9	12.1	0	0	230	142.5
12	11	10.6	0	9.9	12.1	0	0	137	84
13	11	10.89	-0.1	9.9	12.1	0	0	72	45

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]	P Load [kW]	Q Load [kVAr]
14	11	10.89	-0.1	9.9	12.1	0	0	72	45
15	11	10.89	-0.1	9.9	12.1	0	0	72	45
16	11	10.89	-0.1	9.9	12.1	0	0	13.5	7.5
17	11	10.67	-0.3	9.9	12.1	0	0	230	142.5
18	11	10.64	-0.4	9.9	12.1	0	0	230	142.5
19	11	10.61	-0.5	9.9	12.1	0	0	230	142.5
2	11	10.94	-0.1	9.9	12.1	0	0	230	142.5
20	11	10.57	-0.6	9.9	12.1	0	0	230	142.5
21	11	10.55	-0.5	9.9	12.1	0	0	230	142.5
22	11	10.51	-0.5	9.9	12.1	0	0	230	142.5
23	11	10.48	-0.5	9.9	12.1	0	0	230	142.5
24	11	10.45	-0.4	9.9	12.1	0	0	230	142.5
25	11	10.44	-0.4	9.9	12.1	0	0	230	142.5
26	11	10.44	-0.4	9.9	12.1	0	0	230	142.5
27	11	10.43	-0.4	9.9	12.1	0	0	137	85
28	11	10.67	-0.1	9.9	12.1	0	0	75	48
29	11	10.67	-0.1	9.9	12.1	0	0	75	48
3	11	10.9	-0.1	9.9	12.1	0	0	0	0
30	11	10.67	-0.1	9.9	12.1	0	0	75	48
31	11	10.61	0	9.9	12.1	0	0	57	34.5
32	11	10.6	0	9.9	12.1	0	0	57	34.5
33	11	10.6	0	9.9	12.1	0	0	57	34.5
34	11	10.6	0	9.9	12.1	0	0	57	34.5
4	11	10.83	-0.1	9.9	12.1	0	0	230	142.5
5	11	10.77	-0.2	9.9	12.1	0	0	230	142.5
6	11	10.72	-0.2	9.9	12.1	0	0	0	0
7	11	10.67	-0.1	9.9	12.1	0	0	0	0
8	11	10.65	-0.1	9.9	12.1	0	0	230	142.5
9	11	10.62	0	9.9	12.1	0	0	230	142.5

Table: 4.41 Line flows, line losses, and line loading (%) for Case 11

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L_15_16	15	16	13.43	7.43	15.35	87.5	0.8	0	0.1
L_25_26	25	26	367.19	227.22	431.81	85	23.9	0.22	4
L_26_27	26	27	137.02	84.87	161.18	85	8.9	0.03	1.5
L_8_9	8	9	828.92	506.19	971.25	85.3	52.7	2.62	8.8
L_13_14	13	14	157.55	97.11	185.07	85.1	9.8	0.06	1.6
L_23_24	23	24	830.85	512.25	976.07	85.1	53.8	2.73	9

Line ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L_33_34	33	34	57.02	34.39	66.59	85.6	3.6	0	0.6
L_7_8	7	8	1061.79	648.95	1244.4	85.3	67.3	2.85	11.2
L_14_15	14	15	85.56	52.34	100.3	85.3	5.3	0.01	0.9
L_24_25	24	25	598.13	369.63	703.12	85.1	38.8	0.95	6.5
L_7_28	7	28	225.16	143.52	267.02	84.3	14.4	0.1	2.4
L_21_22	21	22	1298.73	341.6	1342.9	96.7	73.5	4.25	12.3
L_31_32	31	32	171.11	103.02	199.73	85.7	10.9	0.07	1.8
L_11_12	11	12	137.05	83.89	160.69	85.3	8.7	0.02	1.5
L_22_23	22	23	1064.52	655.1	1249.94	85.2	68.7	3.7	11.4
L_32_33	32	33	113.99	68.72	133.11	85.6	7.2	0.02	1.2
L_10_11	10	11	367.22	226.26	431.33	85.1	23.5	0.22	3.9
L_10_31	10	31	228.19	137.37	266.35	85.7	14.5	0.1	2.4
L_29_30	29	30	75.01	47.83	88.97	84.3	4.8	0.01	0.8
L_19_20	19	20	1768.32	-64.75	1769.5	99.9	96.3	5.26	16.1
L_20_21	20	21	1533.07	484.82	1607.9	95.3	87.8	4.37	14.6
L_2_3	2	3	4552.59	916.65	4643.96	98	245	19.31	40.8
L_3_13	3	13	229.69	141.96	270.02	85.1	14.3	0.1	2.4
L_1_2	1	2	4806.1	1068.44	4923.43	97.6	258.4	23.44	43.1
L_9_10	9	10	596.32	363.58	698.41	85.4	38	0.91	6.3
L_6_7	6	7	1293.22	793.24	1517.11	85.2	81.7	6.3	13.6
L_6_17	6	17	2483.73	-328.74	2505.39	99.1	135	9.81	22.5
L_5_6	5	6	3795.82	469.45	3824.74	99.2	205	18.86	34.2
L_4_5	4	5	4047.17	617.58	4094.02	98.9	218.3	21.37	36.4
L_17_18	17	18	2243.93	-473.59	2293.37	97.8	124	7.59	20.7
L_28_29	28	29	150.03	95.67	177.94	84.3	9.6	0.04	1.6
L_18_19	18	19	2006.35	-617.86	2099.33	95.6	113.9	8.09	19
L_3_4	3	4	4303.66	767.1	4371.5	98.4	231.6	26.47	38.6

Table 4.42 Loss sensitivity factors arranged in descending order for Case 11

Order	LSI	Start bus	End bus	Vi, p.u.	Vj, p.u.	Vnorm	Compensation required at bus no.
1	0.007304	6	7	0.974	0.97	1.0210526	--
2	0.006634	22	23	0.956	0.953	1.0031579	--
3	0.005523	7	8	0.97	0.968	1.0189474	--
4	0.004768	23	24	0.953	0.95	1	24
5	0.004622	8	9	0.968	0.966	1.0168421	--
6	0.004603	29	30	0.97	0.97	1.0210526	--
7	0.004026	3	4	0.991	0.984	1.0357895	--
8	0.003839	24	25	0.95	0.949	0.9989474	25

Order	LSI	Start bus	End bus	Vi, p.u.	Vj, p.u.	Vnorm	Compensation required at bus no.
9	0.003713	9	10	0.966	0.965	1.0157895	--
10	0.003545	1	2	1	0.995	1.0473684	--
11	0.003063	4	5	0.984	0.979	1.0305263	--
12	0.00293	2	3	0.995	0.991	1.0431579	--
13	0.002796	11	12	0.964	0.964	1.0147368	--
14	0.002578	5	6	0.979	0.974	1.0252632	--
15	0.001923	25	26	0.949	0.949	0.9989474	26
16	0.00186	10	11	0.965	0.964	1.0147368	--
17	0.000962	26	27	0.949	0.949	0.9989474	27
18	0.000942	21	22	0.959	0.956	1.0063158	22
19	0.000932	31	32	0.964	0.964	1.0147368	--
20	0.000932	32	33	0.964	0.964	1.0147368	--
21	0.000921	7	28	0.97	0.97	1.0210526	--
22	0.000884	14	15	0.99	0.99	1.0421053	--
23	0.000884	13	14	0.99	0.99	1.0421053	--
24	0.000882	3	13	0.991	0.99	1.0421053	--
25	0.000677	20	21	0.961	0.959	1.0094737	--
26	0.000668	18	19	0.967	0.964	1.0147368	--
27	0	33	34	0.964	0.964	1.0147368	--
28	0	19	20	0.964	0.961	1.0115789	--
29	0	15	16	0.99	0.99	1.0421053	--
30	-0.00093	10	31	0.965	0.964	1.0147368	--
31	-0.00156	6	17	0.974	0.97	1.0210526	--
32	-0.00263	17	18	0.97	0.967	1.0178947	--
33	-0.00552	28	29	0.97	0.97	1.0210526	--

So, it is found that the following buses need capacitor compensation in the following sequence: {24,25,26,27,22}. The most responsive bus {24} is selected for placement of capacitor. After several attempt, it is found that the when 350 kVAr is added at bus 24, the loss reduction is maximum i.e it becomes 167.6 kW. If further amount of capacitor is added, the loss increases. So, we stop our search for optimum sizing of capacitor here.

The cost function is also found to be positive for this combination of capacitors. So, capacitor compensation is made at the following bus:

a. Bus 19=750 kVAr
b. Bus 22=500 kVAr

c. Bus 20=750 kVAr
d. Bus 24=350 kVAr

Cost Analysis &Verification of the worthiness of investment

Eqn. 3.6 to 3.9 and corresponding notations of chapter 3 are referred. Using these Eqns. worthiness of investment for installation of 750 kVAr capacitors at following buses is verified:

a. Bus 19=750 kVAr
b. Bus 22=500 kVAr
c. Bus 20=750 kVAr
d. Bus 24=350 kVAr

Before Compensation Cost of Energy Loss Calculation

Total power loss, P_L: 221.4 kW

Total cost of energy loss, E1:BDT 6,01,23,384.00

After Compensation Cost of Energy Loss Calculation

Total power loss,P_L: 167.6 kW

Total cost of energy loss, E2: BDT 4,55,13,456.00

Net cost of energy saved, E= BDT 1,46,09,928.00

Calculation for Cost of Investment

kVAr added in the system: 2350 kVAr

No. of locations: 4

Total Capacitor purchase cost, C_{cost}: BDT 1,17,50,000.00

Total Installation cost, I_{cost}: BDT 1,20,000.00

Total Operation and maintenance cost, OM_{cost}: BDT 2,00,000.00

Total cost of investment, I= BDT 1,20,70,000.00

Difference between cost of energy saved and total cost of investment= BDT 25,39,928.00

The difference is positive, so investment up to this amount of kVAr (2350 kVAr) is acceptable.

4.4.2 Winter off peak loading condition

Case 12

After necessary parameters are inserted in to database of the PSAF and completion of drawing of IEEE 34 bus distribution network, the base case load flow is run without adding any capacitor to the network. The winter off peak load is assumed to be 60% of summer peak load. From the simulation result, the bus voltages, bus loads, line flows, lineloading and LSF are collected/calculated and shown in table 4.43 to 4.46

Table 4.43Bus Voltages for Case 12

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
1	11	11	0	9.9	12.1	2858.49	1739.17
10	11	10.75	0.4	9.9	12.1	0	0
11	11	10.74	0.4	9.9	12.1	0	0
12	11	10.74	0.4	9.9	12.1	0	0
13	11	10.93	0.1	9.9	12.1	0	0
14	11	10.92	0.1	9.9	12.1	0	0
15	11	10.92	0.1	9.9	12.1	0	0
16	11	10.92	0.1	9.9	12.1	0	0
17	11	10.78	0.3	9.9	12.1	0	0
18	11	10.76	0.3	9.9	12.1	0	0
19	11	10.73	0.4	9.9	12.1	0	0
2	11	10.96	0	9.9	12.1	0	0
20	11	10.71	0.4	9.9	12.1	0	0
21	11	10.69	0.4	9.9	12.1	0	0
22	11	10.67	0.5	9.9	12.1	0	0
23	11	10.65	0.5	9.9	12.1	0	0
24	11	10.64	0.6	9.9	12.1	0	0

Bus ID	kV Base	V sol [kV]	Ang sol [deg]	Vmin [kV]	Vmax [kV]	P Gen [kW]	Q Gen [kVAr]
25	11	10.63	0.6	9.9	12.1	0	0
26	11	10.62	0.6	9.9	12.1	0	0
27	11	10.62	0.6	9.9	12.1	0	0
28	11	10.78	0.3	9.9	12.1	0	0
29	11	10.78	0.3	9.9	12.1	0	0
3	11	10.93	0.1	9.9	12.1	0	0
30	11	10.78	0.3	9.9	12.1	0	0
31	11	10.74	0.4	9.9	12.1	0	0
32	11	10.74	0.4	9.9	12.1	0	0
33	11	10.74	0.4	9.9	12.1	0	0
34	11	10.74	0.4	9.9	12.1	0	0
4	11	10.88	0.1	9.9	12.1	0	0
5	11	10.85	0.2	9.9	12.1	0	0
6	11	10.81	0.2	9.9	12.1	0	0
7	11	10.78	0.3	9.9	12.1	0	0
8	11	10.77	0.3	9.9	12.1	0	0
9	11	10.75	0.4	9.9	12.1	0	0

Table 4.44 Bus Loads for Case 12

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L30	30	45	28.8	53.43	84.2
L20	20	138	85.5	162.34	85
L31	31	34.2	20.7	39.98	85.6
L11	11	138	85.5	162.34	85
L21	21	138	85.5	162.34	85
L32	32	34.2	20.7	39.98	85.6
L12	12	82.2	50.4	96.42	85.3
L22	22	138	85.5	162.34	85
L33	33	34.2	20.7	39.98	85.6
L13	13	43.2	27	50.94	84.8
L23	23	138	85.5	162.34	85
L34	34	34.2	20.7	39.98	85.6
L14	14	43.2	27	50.94	84.8
L24	24	138	85.5	162.34	85
L15	15	43.2	27	50.94	84.8
L25	25	138	85.5	162.34	85
L16	16	8.1	4.5	9.27	87.4
L26	26	138	85.5	162.34	85

Load ID	Bus ID	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]
L17	17	138	85.5	162.34	85
L27	27	82.2	51	96.74	85
L28	28	45	28.8	53.43	84.2
L18	18	138	85.5	162.34	85
L29	29	45	28.8	53.43	84.2
L19	19	138	85.5	162.34	85
L2	2	138	85.5	162.34	85
L4	4	138	85.5	162.34	85
L5	5	138	85.5	162.34	85
L8	8	138	85.5	162.34	85
L9	9	138	85.5	162.34	85

Table: 4.45Line flows, line losses, and line loading (%) for Case 12

ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L_15_16	15	16	8.12	4.45	9.25	87.7	0.5	0	0.1
L_25_26	25	26	220.25	136.25	258.99	85	14.1	0.08	2.3
L_26_27	26	27	82.18	50.88	96.66	85	5.3	0.01	0.9
L_8_9	8	9	496.38	302.96	581.53	85.4	31.2	0.92	5.2
L_13_14	13	14	94.52	58.1	110.95	85.2	5.9	0.02	1
L_23_24	23	24	497.55	306.92	584.6	85.1	31.7	0.95	5.3
L_33_34	33	34	34.22	20.59	39.94	85.7	2.1	0	0.4
L_7_8	7	8	635.38	388.41	744.7	85.3	39.9	1	6.6
L_14_15	14	15	51.34	31.34	60.14	85.4	3.2	0	0.5
L_24_25	24	25	358.63	221.59	421.57	85.1	22.9	0.33	3.8
L_7_28	7	28	135.05	85.91	160.06	84.4	8.6	0.03	1.4
L_11_12	11	12	82.16	50.28	96.32	85.3	5.2	0.01	0.9
L_21_22	21	22	776.73	477.92	911.99	85.2	49.3	1.91	8.2
L_31_32	31	32	102.66	61.61	119.73	85.7	6.4	0.03	1.1
L_22_23	22	23	636.82	392.36	747.99	85.1	40.5	1.29	6.7
L_32_33	32	33	68.37	41.12	79.78	85.7	4.3	0.01	0.7
L_10_11	10	11	220.29	135.66	258.71	85.1	13.9	0.08	2.3
L_20_21	20	21	916.66	563.58	1076.05	85.2	58	1.91	9.7
L_19_20	19	20	1057.17	649.38	1240.69	85.2	66.8	2.53	11.1
L_10_31	10	31	136.84	82.14	159.6	85.7	8.6	0.03	1.4
L_29_30	29	30	45.02	28.64	53.36	84.4	2.9	0	0.5
L_2_3	2	3	2709.67	1649.57	3172.29	85.4	167.1	8.98	27.8
L_3_13	3	13	137.74	84.94	161.82	85.1	8.5	0.03	1.4
L_1_2	1	2	2858.51	1739.17	3346.01	85.4	175.6	10.83	29.3

ID	Bus From	Bus To	P [kW]	Q [kVAr]	S [kVA]	P. Factor [%]	I [A]	P losses [kW]	Loading %
L_9_10	9	10	357.49	217.64	418.53	85.4	22.5	0.32	3.7
L_6_7	6	7	772.66	474.37	906.65	85.2	48.4	2.21	8.1
L_6_17	6	17	1482.85	908.02	1738.78	85.3	92.9	4.64	15.5
L_5_6	5	6	2264.44	1384.6	2654.21	85.3	141.3	8.96	23.6
L_4_5	4	5	2412.52	1472.62	2826.46	85.4	149.9	10.08	25
L_17_18	17	18	1340.23	821.56	1572	85.3	84.2	3.5	14
L_18_19	18	19	1198.69	735.38	1406.29	85.2	75.5	3.55	12.6
L_28_29	28	29	90.02	57.27	106.7	84.4	5.7	0.02	1
L_3_4	3	4	2562.91	1561.25	3001.01	85.4	158.5	12.4	26.4

Table 4.46 Loss sensitivity factors arranged in descending order for Case 12

Order	LSI	Start bus	End bus	V_i (p.u)	V_j (p.u)	V_{norm} (p.u)	Compensation required at bus no.
1	0.008003	3	4	0.994	0.989	1.04105263	--
2	0.007579	4	5	0.989	0.986	1.03789474	--
3	0.007117	5	6	0.986	0.983	1.03473684	--
4	0.005479	1	2	1	0.997	1.04947368	--
5	0.005188	2	3	0.997	0.994	1.04631579	--
6	0.004603	6	17	0.983	0.98	1.03157895	--
7	0.004584	21	22	0.972	0.97	1.02105263	--
8	0.004573	18	19	0.978	0.975	1.02631579	--
9	0.004482	6	7	0.983	0.98	1.03157895	--
10	0.004117	17	18	0.98	0.978	1.02947368	--
11	0.00396	20	21	0.973	0.972	1.02315789	--
12	0.003943	19	20	0.975	0.973	1.02421053	--
13	0.003682	22	23	0.97	0.968	1.01894737	--
14	0.003607	7	8	0.98	0.979	1.03052632	--
15	0.002773	23	24	0.968	0.967	1.01789474	--
16	0.002711	8	9	0.979	0.978	1.02947368	--
17	0.001852	24	25	0.967	0.966	1.01684211	--
18	0.001811	9	10	0.978	0.977	1.02842105	--
19	0.000928	25	26	0.966	0.966	1.01684211	--
20	0.000928	26	27	0.966	0.966	1.01684211	--
21	0.000907	11	12	0.977	0.977	1.02842105	--
22	0.000907	31	32	0.977	0.977	1.02842105	--
23	0.000907	10	31	0.977	0.977	1.02842105	--
24	0.000907	10	11	0.977	0.977	1.02842105	--
25	0.000902	28	29	0.98	0.98	1.03157895	--
26	0.000902	7	28	0.98	0.98	1.03157895	--

Order	LSI	Start bus	End bus	V_i (p.u)	V_j (p.u)	V_{norm} (p.u)	Compensation required at bus no.
27	0.000878	13	14	0.993	0.993	1.04526316	--
28	0.000877	3	13	0.994	0.993	1.04526316	--
29	0	15	16	0.993	0.993	1.04526316	--
30	0	33	34	0.976	0.976	1.02736842	--
31	0	14	15	0.993	0.993	1.04526316	--
32	0	32	33	0.977	0.976	1.02736842	--
33	0	29	30	0.98	0.98	1.03157895	--

So, it is found from table 5.37 that all the buses are having healthy voltages and none of them requires any reactive compensation. Total loss is 76.65 kW.

Chapter 5

PERFORMANCE ANALYSIS

5.1 Introduction

In this chapter the result of simulation of IEEE 9 bus, IEEE 15 bus and IEEE 34 bus networks are analyzed and performance of proposed methodology is compared with other techniques mentioned in the references. Performance for summer peak loading condition presented. Followings attributes, obtained before and after compensation, are compared:

a. Voltage profile before and after compensation
b. Conductor ampere loading (%) before and after compensation. It is shown to give an idea how much conductor capacity is freed up.
c. Line losses (kW) before and after compensation
d. Average power factor before and after compensation.

Finally, the proposed technique is evaluated by comparing the performance obtained using established techniques.

5.2 Performance of Proposed Technique

5.2.1 IEEE 9 bus network

Figures 5.1 to 5.4 present the comparison of the voltage profile, conductor loading, line losses, and average power factor before compensation and after compensation for the IEEE 9 Bus System using the proposed technique.

It can be see that-

a. Minimum voltage before compensation is 0.838 (p.u) where as it is 0.9 (p.u) after compensation at bus 9.
b. Voltage at each bus except the swing bus increases after compensation. This increase in voltage is more prominent at those buses which are far away from swing bus.

c. Line capacity is found to have been freed up after compensation. It indicates that the transmission capacity of each line has been increased after compensation.
d. The same conductor used in the line can now transmit more power. As a result, the distribution utility does not need to change the existing line or does not need to overload the existing line to transmit more power.
e. The line loss is also found to have been reduced for each line of IEEE 9 Bus System after compensation. Before compensation line loss is 783.65 kW whereas this amount is 685 kW after compensation. It indicates that placement of shunt capacitor using the proposed methodology can reduce the system loss by 12.5% which is quite significant.
f. The distribution utility is directly benefitted through reduction of system loss. The reduction in system loss helps distribution utilities to achieve their annual KPI (Key Performance Indicator) target.
g. The average power factor is also found to have been improved significantly. The improved power factor allows the utility to avoid penalty due to poor power factor.

In general it can be said that placement of shunt capacitor at optimum location improves voltage profile, increases transmission capacity of line, reduces line losses and enhances power factor of the entire network. It helps distribution utility to provide quality power to its customers.

Table 5.1: Bus voltage before and after compensation for IEEE 9 bus network

Bus ID	Voltage before compensation (p.u)	Voltage after compensation (p.u)
1	1	1
2	0.993	0.997
3	0.987	0.998
4	0.963	0.986
5	0.948	0.977
6	0.917	0.96
7	0.907	0.954
8	0.889	0.94
9	0.859	0.919
10	0.838	0.9

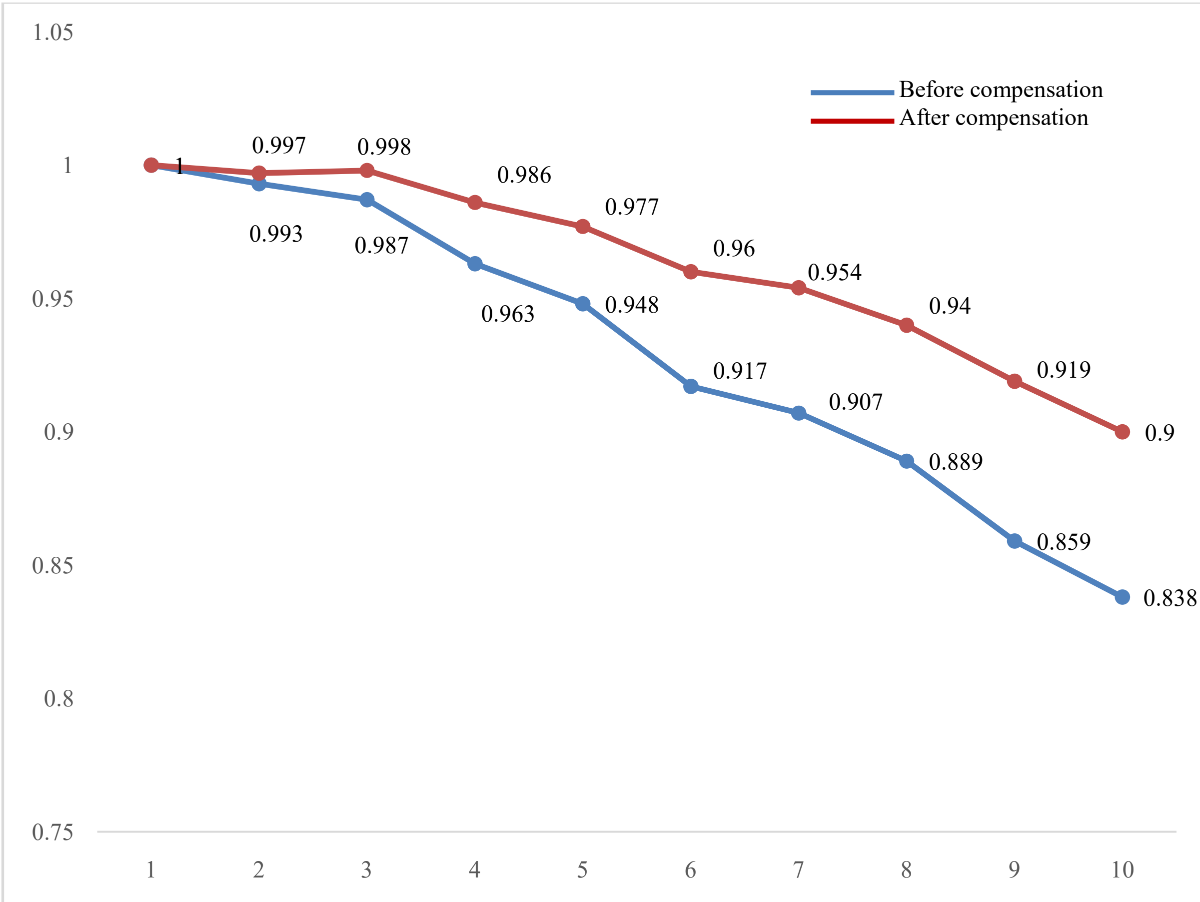


Fig 5.1: Voltage profile in p.u.before and after compensation for IEEE 9 bus network

Table 5.2: Line loading (%) before and after compensation for IEEE 9 bus network

X axis Sl. No. in Fig 5.2	Line ID	Loading (%) before compensation	Loading (%) after compensation
1	L1	59.2	54.6
2	L2	51.3	47
3	L3	46.9	42.9
4	L4	39	35.8
5	L5	29.9	29.2
6	L6	22.1	21.3
7	L7	18.5	17
8	L8	13	12
9	L9	8.2	7.3

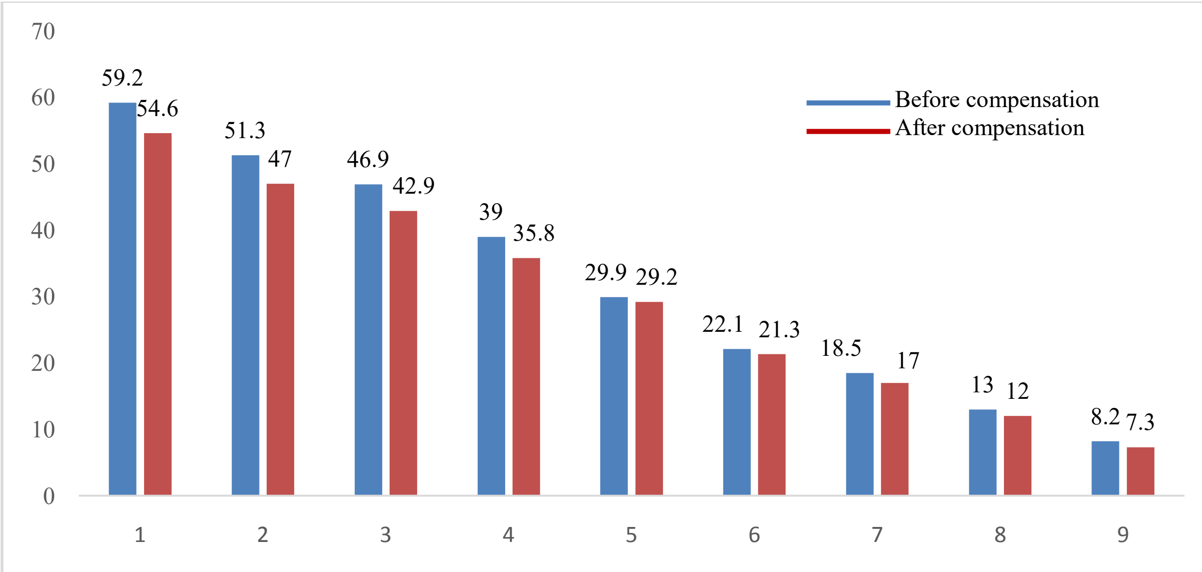


Fig 5.2: Line ampere loading (%) before and after compensation for IEEE 9 bus network

Table 5.3: Line loss (kW) before and after compensation for IEEE 9 bus network

X axis Sl. No. in Fig 5.3	Line ID	Line Loss before compensation	Line Loss after compensation
1	L1	46.61	39.64
2	L2	3.98	3.33
3	L3	176.98	148.33
4	L4	114.57	96.49
5	L5	191.08	182.75
6	L6	47.87	44.21
7	L7	75.73	64.5
8	L8	88.07	75.12
9	L9	38.76	30.62
	Total Loss	**783.65**	**685**

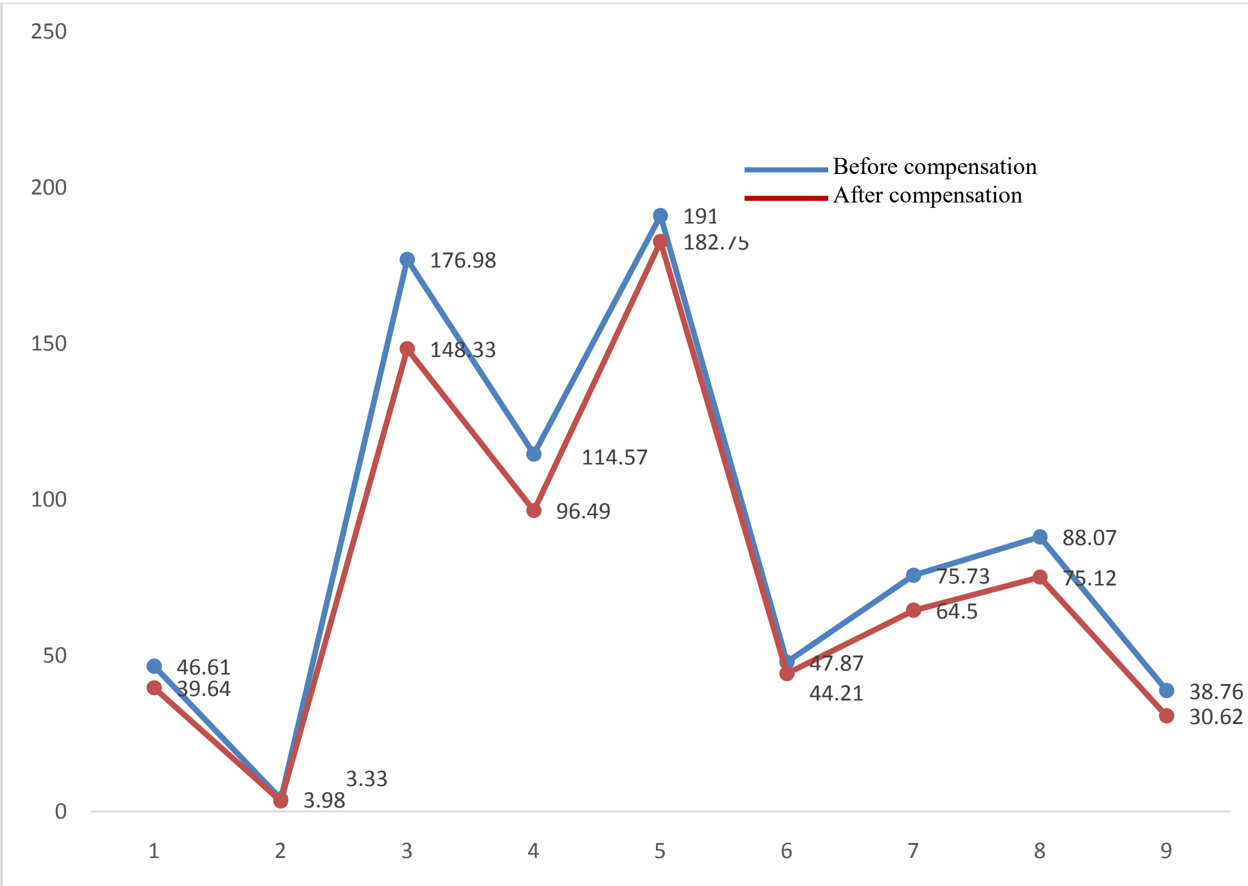


Fig 5.3: Line loss (kW) before and after compensation for IEEE 9 bus network

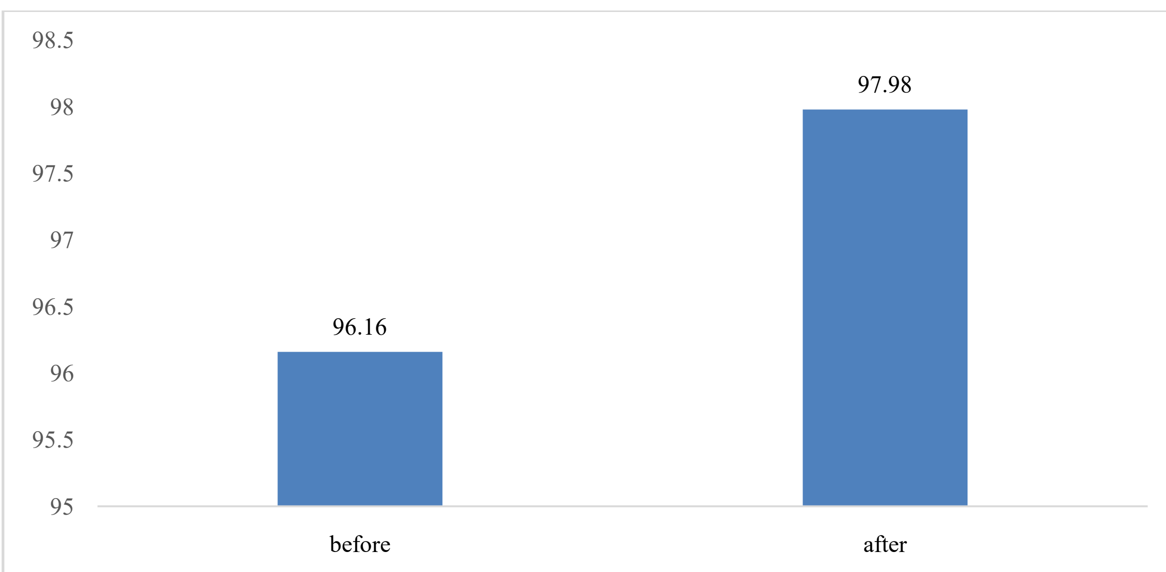


Fig 5.4: Average power factor before and after compensation for IEEE 9 bus network

5.2.2 IEEE 15 bus network

Figures 5.5 to 5.8 present the comparison of the voltage profile, conductor loading, losses, and average power factor before compensation and after compensation for the IEEE 15 bus system using the proposed technique.

It can be see that-

a. Minimum voltage before compensation is 0.945 (p.u) where as it is 0.97 (p.u) after compensation at bus 5.
b. Voltage at each bus except the swing bus increases after compensation. This increase in voltage is more prominent at those buses which are far away from swing bus.
c. Line capacity is found to have been freed up after compensation. It indicates that the transmission capacity of each line has been increased after compensation.
d. The same conductor used in the line can now transmit more power. As a result, the distribution utility does not need to change the existing line or does not need to overload the existing conductor to transmit more power.
e. The line loss is also found to have been reduced for each line of IEEE 15 Bus System after compensation. Before compensation line loss is 61.4 kW whereas this amount is 31.6 kW after compensation. It indicates that placement of shunt capacitor using the proposed methodology can reduce the system loss by 48.53% which is quite significant.
f. The distribution utility is directly benefitted through reduction of system loss. The reduction in system loss helps distribution utilities to achieve their annual KPI (Key Performance Indicator) target.
g. The average power factor is also found to have been improved significantly. The improved power factor allows the utility to avoid penalty due to poor power factor.

In general it can be said that placement of shunt capacitor at optimum location improves voltage profile, increases transmission capacity of line, reduces line losses and enhances power factor of the entire network. It helps distribution utility to provide quality power to its customers.

Table 5.4: Bus voltage before and after compensation for IEEE 15 bus network

X axis S.l. No. in fig 5.5	Bus ID	Voltage before compensation (p.u)	Voltage after compensation (p.u)
1	B1	1	1
2	B10	0.967	0.981
3	B11	0.95	0.975
4	B12	0.946	0.971
5	B13	0.945	0.97
6	B14	0.949	0.971
7	B15	0.949	0.971
8	B2	0.971	0.986
9	B3	0.957	0.979
10	B4	0.951	0.973
11	B5	0.95	0.972
12	B6	0.958	0.98
13	B7	0.956	0.978
14	B8	0.957	0.979
15	B9	0.968	0.982

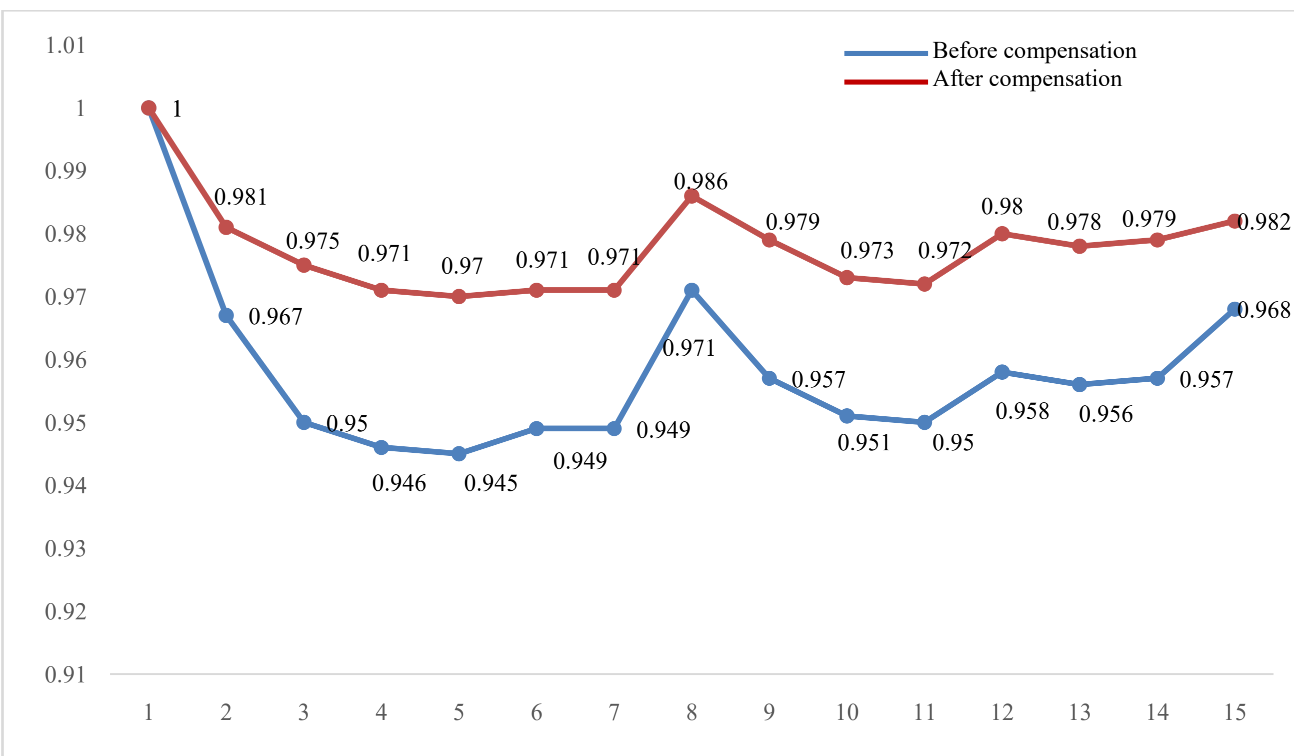


Fig 5.5: Voltage profile (in p.u) before and after compensation for IEEE 15 bus network

Table 5.5: Loading (%) before and after compensation for IEEE 15 bus network

X axis Sl. No. in Fig 5.6	Line ID	Loading (%) before compensation	Loading (%) after compensation
1	L10	5	3.4
2	L11	2.3	2.2
3	L12	0.9	0.8
4	L13	1.4	1.3
5	L14	2.8	2.7
6	L1	24	16.5
7	L2	14.1	9.7
8	L3	7.8	7.6
9	L4	0.9	0.8
10	L5	2.2	2.2
11	L6	0.8	0.8
12	L7	6.8	5
13	L8	2.7	2.7
14	L9	1.4	1.3

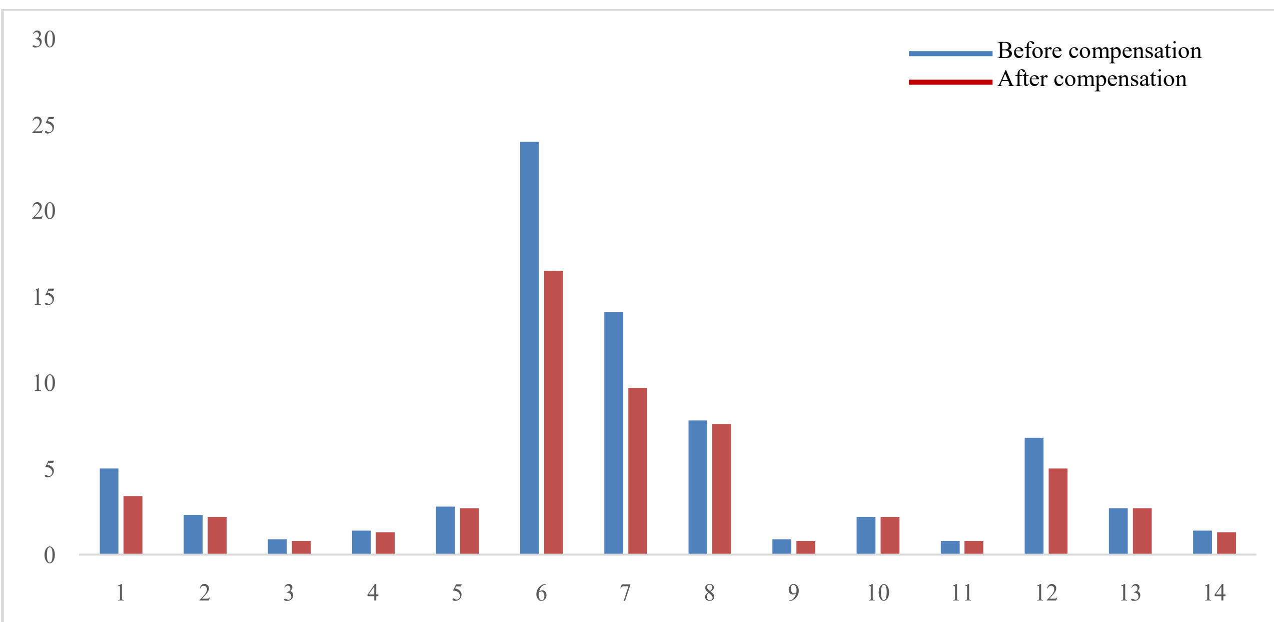


Fig 5.6: Line ampere loading (%) before and after compensation for IEEE 15 bus network

Table 5.6: Line loss (kW) before and after compensation for IEEE 15 bus network

X axis Sl. No. in Fig 5.7	Line ID	Line Loss before compensation	Line Loss after compensation
1	L10	2.17	1.02
2	L11	0.6	0.57
3	L12	0.07	0.07
4	L13	0.2	0.19
5	L14	0.44	0.42
6	L1	37.42	17.68
7	L2	11.23	5.28
8	L3	2.43	2.32
9	L4	0.06	0.05
10	L5	0.47	0.45
11	L6	0.06	0.06
12	L7	5.75	3.04
13	L8	0.39	0.38
14	L9	0.11	0.11
Total Loss		**61.4**	**31.64**

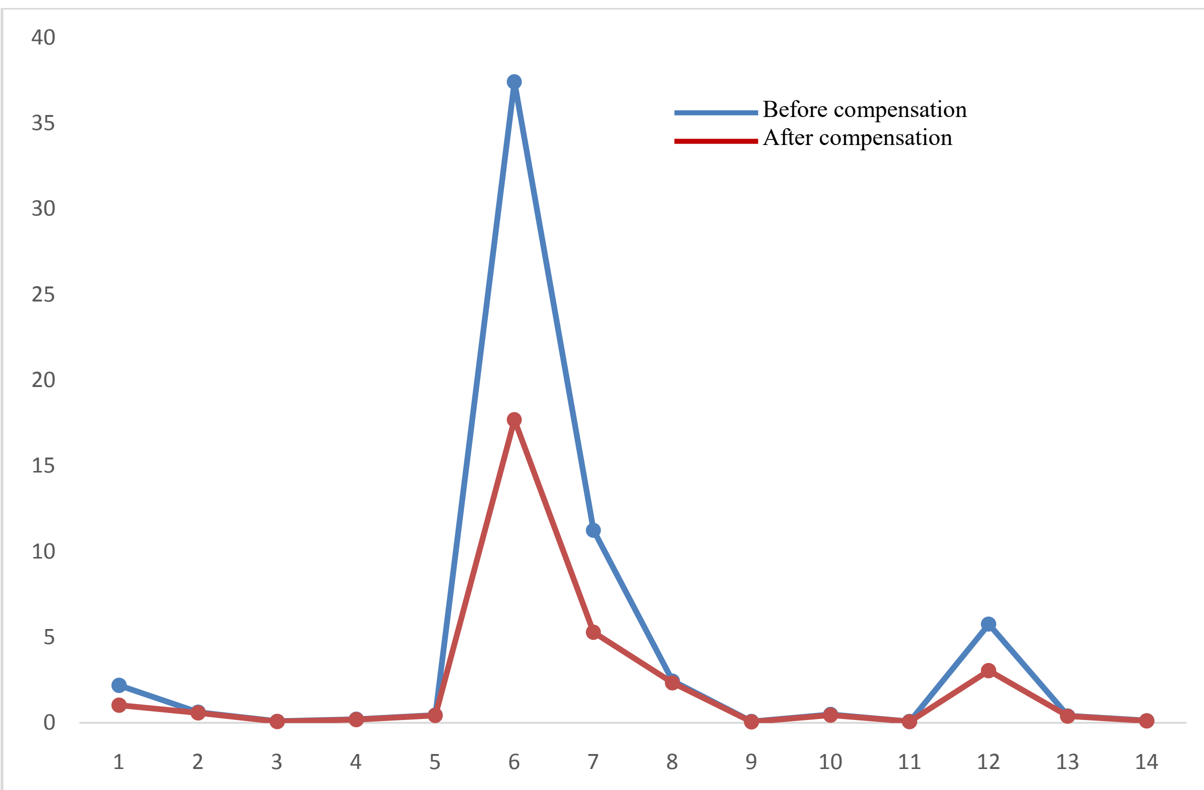


Fig 5.7: Line loss (kW) before and after compensation for IEEE 15bus network

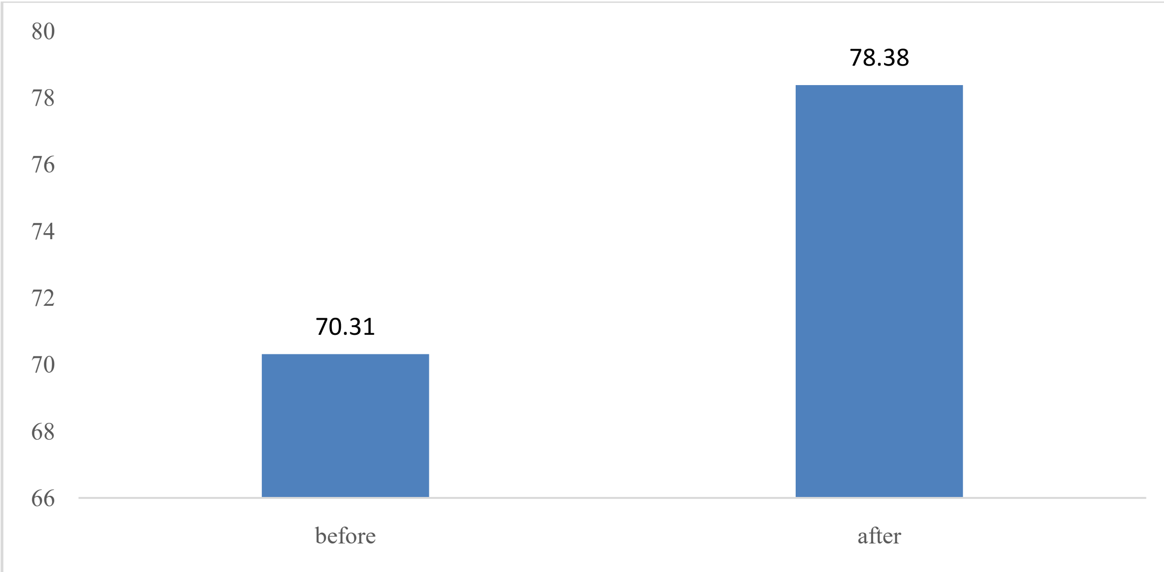


Fig 5.8: Average power factor before and after compensation for IEEE 15bus network

5.2.3 IEEE 34 bus network

Figures 5.9 to 5.12 present the comparison of the voltage profile, conductor loading, losses, and average power factor before compensation and after compensation for the IEEE 34 bus system using the proposed technique.

It can be see that-

a. Minimum voltage before compensation is 0.942 (p.u) where as it is 0.95 (p.u) after compensation at bus 27.
b. Voltage at each bus except the swing bus increases after compensation. This increase in voltage is more prominent at those buses which are far away from swing bus.
c. Line capacity is found to have been freed up after compensation. It indicates that the transmission capacity of each line has been increased after compensation.
d. The same conductor used in the line can now transmit more power. As a result, the distribution utility does not need to change the existing line or does not need to overload the existing conductor to transmit more power.

e. The line loss is also found to have been reduced for each line of IEEE 34 Bus System after compensation. Before compensation line loss is 221.4 kW where as this amount is 167.6 kW after compensation. It indicates that placement of shunt capacitor using the proposed methodology can reduce the system loss by 24.3% which is quite significant.

f. The distribution utility is directly benefitted through reduction of system loss. The reduction in system loss helps distribution utilities to achieve their annual KPI (Key Performance Indicator) target.

g. The average power factor is also found to have been improved significantly. The improved power factor allows the utility to avoid penalty due to poor power factor.

In general it can be said that placement of shunt capacitor at optimum location improves voltage profile, increases transmission capacity of line, reduces line losses and enhances power factor of the entire network. It helps distribution utility to provide quality power to its customers.

Table 5.7: Voltage profile before and after compensation for IEEE 34 bus network

X axis Sl. No. in fig 5.9	Bus ID	Voltage before compensation (p.u)	Voltage after compensation (p.u)
1	1	1	1
2	10	0.961	0.965
3	11	0.96	0.965
4	12	0.96	0.965
5	13	0.989	0.99
6	14	0.988	0.99
7	15	0.988	0.99
8	16	0.988	0.99
9	17	0.966	0.971
10	18	0.962	0.968
11	19	0.958	0.965
12	2	0.994	0.995
13	20	0.955	0.962
14	21	0.952	0.96
15	22	0.949	0.957
16	23	0.946	0.954
17	24	0.944	0.952
18	25	0.942	0.951
19	26	0.942	0.95

X axis Sl. No. in fig 5.9	Bus ID	Voltage before compensation (p.u)	Voltage after compensation (p.u)
20	27	0.942	0.95
21	28	0.966	0.971
22	29	0.966	0.97
23	3	0.989	0.991
24	30	0.966	0.97
25	31	0.961	0.965
26	32	0.96	0.964
27	33	0.96	0.964
28	34	0.96	0.964
29	4	0.982	0.985
30	5	0.976	0.98
31	6	0.97	0.975
32	7	0.967	0.971
33	8	0.965	0.969
34	9	0.962	0.966

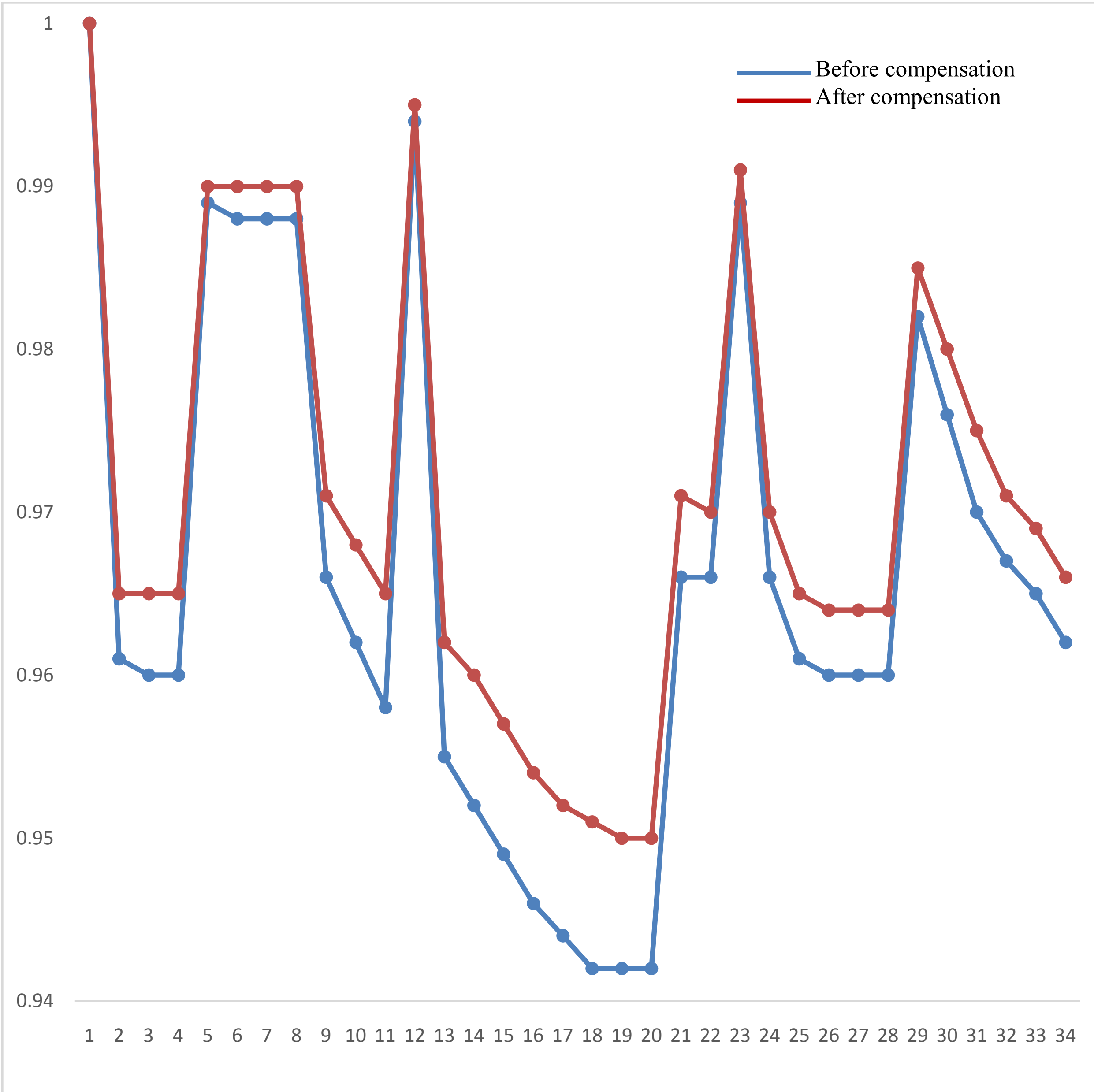


Fig 5.9: Voltage profile (in p.u) before and after compensation for IEEE 34 bus network

Table 5.8: Line ampere loading (%) before and after compensation for IEEE 34 bus network

X axis Sl. No. in fig 5.10	line	Loading (%) before compensation	Loading (%) after compensation
1	L_15_16	0.2	0.2
2	L_25_26	6	6
3	L_26_27	2.2	2.2
4	L_8_9	13.2	13.2
5	L_13_14	2.5	2.5
6	L_23_24	0.9	0.9
7	L_33_34	13.5	11.7
8	L_7_8	16.9	16.8
9	L_14_15	3.6	3.6
10	L_24_25	1.3	1.3
11	L_7_28	9.8	9.7
12	L_11_12	2.2	2.2
13	L_21_22	2.7	2.7
14	L_31_32	21	17.7
15	L_22_23	1.8	1.8
16	L_32_33	17.3	15.3
17	L_10_11	5.9	5.9
18	L_20_21	1.2	1.2
19	L_19_20	3.6	3.6
20	L_10_31	28.5	24.6
21	L_29_30	24.8	21
22	L_2_3	70.9	60.5
23	L_3_13	3.6	3.6
24	L_1_2	74.4	63.8
25	L_9_10	9.5	9.5
26	L_6_7	20.5	20.4
27	L_6_17	39.5	34.6
28	L_5_6	60	50.9
29	L_4_5	63.7	54.1
30	L_17_18	2.4	2.4
31	L_18_19	35.9	32.2
32	L_28_29	32.2	30
33	L_3_4	67.3	57.3

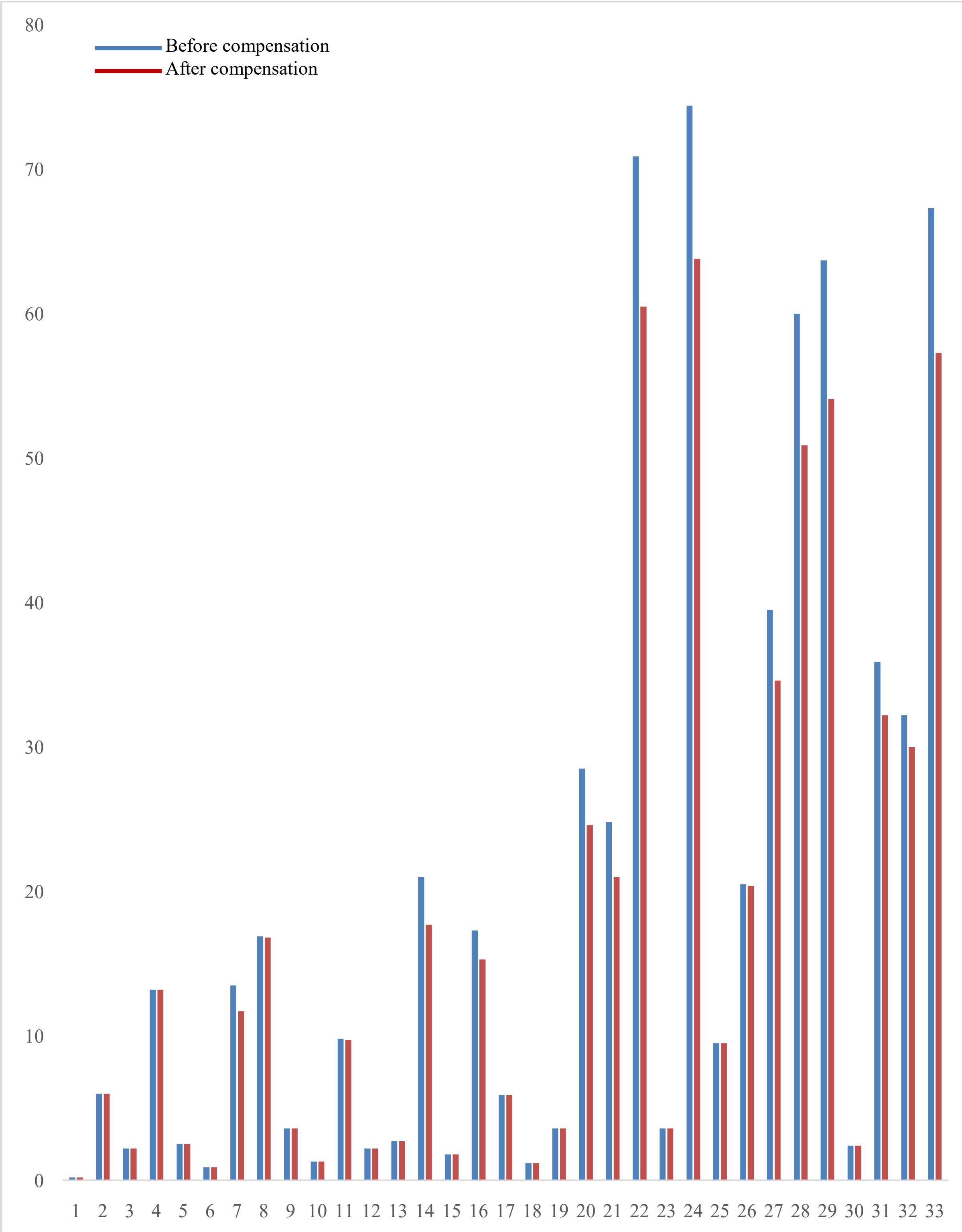


Fig 5.10: Line ampere loading (%) before and after compensation for IEEE 34 bus network

Table5.9: Line loss (kW) before and after compensation for IEEE 34 bus network

X axis Sl. No. in fig 5.11	Line	Line loss before compensation (kW)	Line loss after compensation (kW)
1	L_15_16	0	0
2	L_25_26	0.23	0.22
3	L_26_27	0.03	0.02
4	L_8_9	2.64	2.61
5	L_13_14	0.06	0.06
6	L_23_24	2.77	0
7	L_33_34	0	2.07
8	L_7_8	2.87	2.85
9	L_14_15	0.01	0.1
10	L_24_25	0.96	0.01
11	L_7_28	0.1	0.94
12	L_11_12	0.02	0.02
13	L_21_22	5.56	0.07
14	L_31_32	0.07	3.95
15	L_22_23	3.76	0.02
16	L_32_33	0.02	2.94
17	L_10_11	0.22	0.22
18	L_20_21	5.56	0.01
19	L_19_20	7.35	0.1
20	L_10_31	0.1	5.48
21	L_29_30	0.01	4
22	L_2_3	25.86	18.86
23	L_3_13	0.1	0.1
24	L_1_2	31.12	22.85
25	L_9_10	0.91	0.9
26	L_6_7	6.35	6.3
27	L_6_17	13.46	10.29
28	L_5_6	25.87	18.58
29	L_4_5	29.1	20.98
30	L_17_18	10.15	0.04
31	L_18_19	10.33	8.16
32	L_28_29	0.04	8.99
33	L_3_4	35.75	25.9
Total Loss		**221.38**	**167.64**

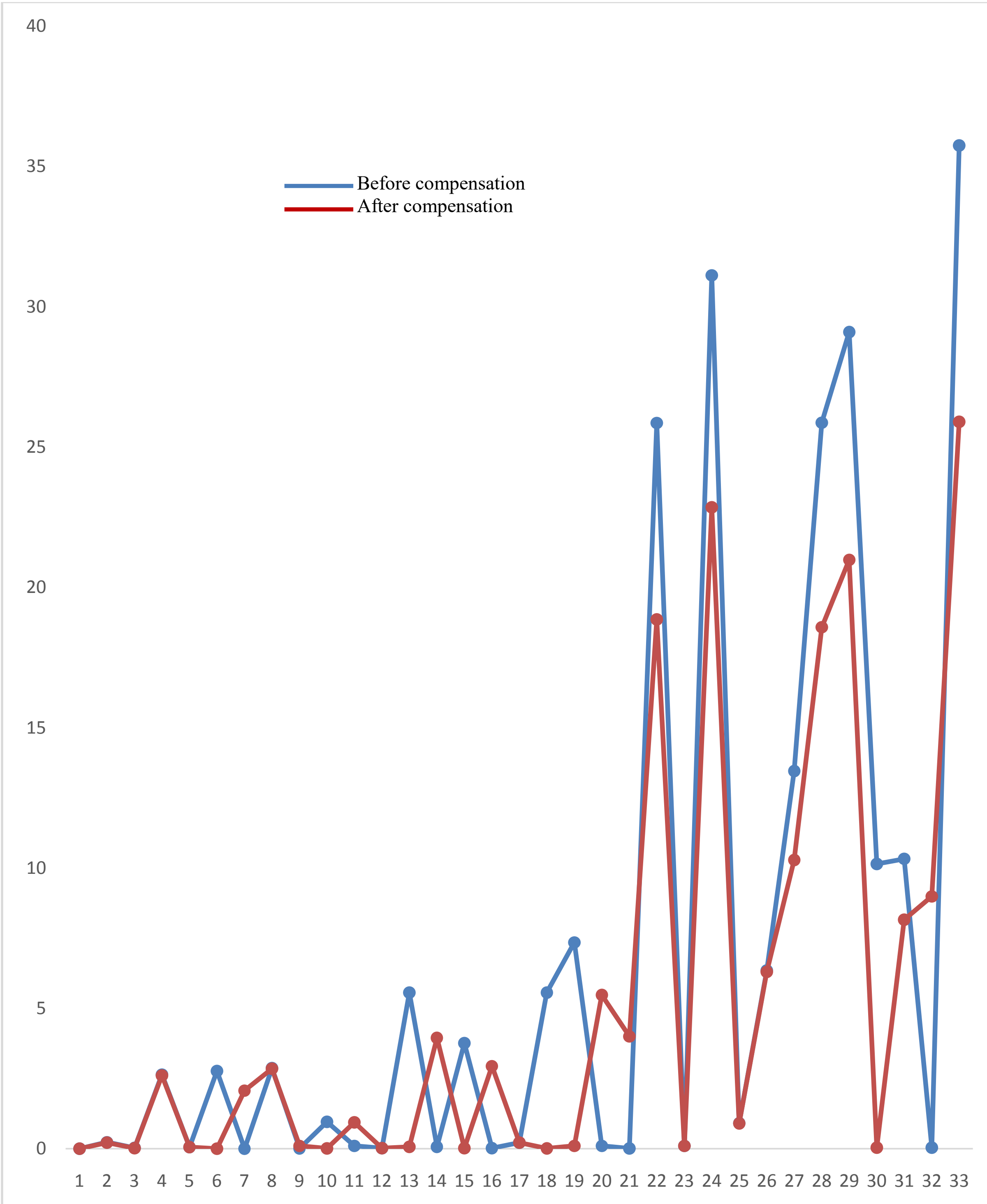


Fig 5.11: Line loss (kW) before and after compensation for IEEE 34 bus network

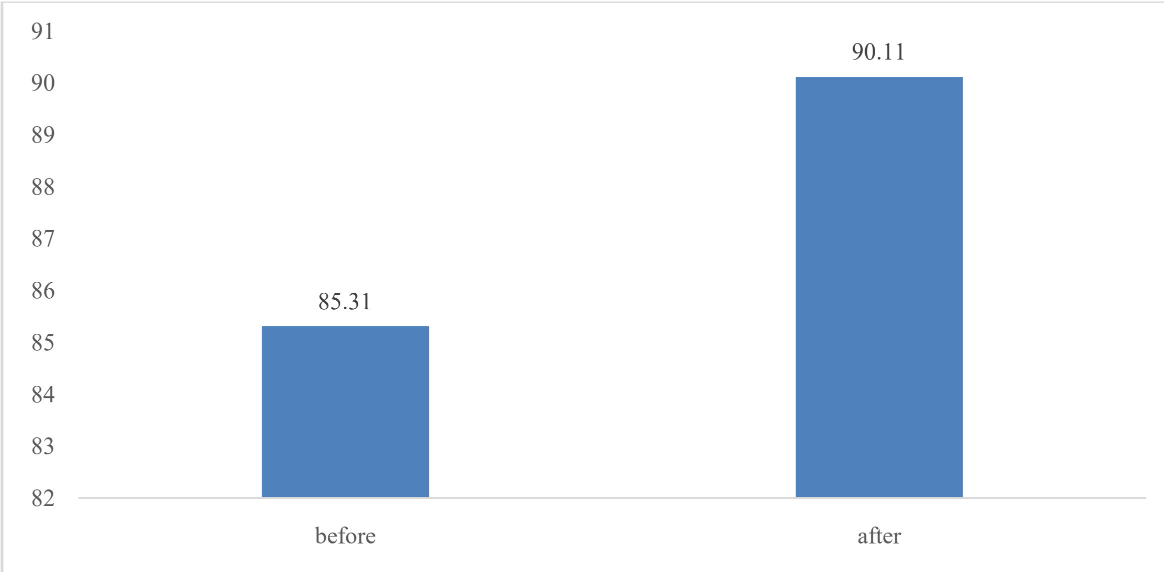


Fig 5.12: Average power factor before and after compensation for IEEE 34 bus network

5.3Performance Comparison with Other Techniques

The performance proposed technique is compared with the performances obtained using established techniques and presented in Tables 5.10 to 5.15. It can be seen that the proposed technique provides a better performance than those reported in literature.The proposed technique reduces the line losses more. It in turn, directly benefits the distribution utility to minimize the system loss. Moreover, the voltages at all buses are also found to have maintained the minimum voltage requirement i.e. 90% of rated voltage.

Table 5.10: Comparison of Performances for 9 bus system

Item	Uncompensated	Compensated						
		Fuzzy Reasoning [26]	GA [12]	PSO [15]	PGSA [4]	FA [38]	ABC [19]	Proposed technique
Total Losses (kW)	783.65	704.88	701.47	696.21	694.93	693.95	693.93	685
Loss Reduction (%)	--	10.065	10.5	11.17	11.33	11.45	11.46	12.5

Table 5.11: Comparison of Performances for 9 bus system

Item	**Compensated**		
	PSO [15]	**ABC [19]**	**Proposed technique**
Minimum Voltage (before) (p.u)	0.8375	0.8375	0.838
Minimum Voltage (after) (p.u)	0.901	0.8715	0.90

Table 5.12: Comparison of Performances for 15 bus system

Item	**Uncompensated**	**Compensated**				
		Heuristic [10]	**PSO [15]**	**FA [38]**	**ABC [19]**	**Proposed technique**
Total Losses (kW)	61.4	32.6	32.7	32.86	32.86	31.6
Loss Reduction (%)	-	46.91	46.74	46.48	46.48	48.53

Table 5.13: Comparison of Performances for 15 bus system

Item	**Compensated**		
	PSO [15]	**ABC [19]**	**Proposed technique**
Minimum Voltage (before)	0.9445	0.9445	0.945
Minimum Voltage (after)	0.9712	0.9676	0.97

Table 5.14: Comparison of Performances for 34 bus system

Item	**Uncompensated**	**Compensated**					
		Heuristic [10]	**FR [26]**	**PSO [15]**	**FA [38]**	**ABC [19]**	**Proposed technique**
Total Losses (kW)	221.4	168.47	168.98	168.8	169.04	168.92	167.6
Loss Reduction (%)	-	23.91	23.68	23.76	23.65	23.7	24.3

Table 5.15: Comparison of Performances for 34 bus system

Item	**Compensated**		
	PSO [15]	**ABC [19]**	**Proposed technique**
Minimum Voltage (before)	0.9417	0.9417	0.942
Minimum Voltage (after)	0.95	0.9492	0.95

Chapter 6

CONCLUSIONS

6.1 Conclusions

A technique for optimal capacitor placement in a radial power distribution system has been proposed in this work. The main endeavour of this work is to improve voltage profile and minimize line losses associated with reactive component of branch currents by placing shunt capacitors in power distribution network. The benefit of the research work also includes improvement of the system power factor and increasing the maximum power flow through lines. By decreasing the flow through lines, the loads of the distribution system can be increased without adding any new lines or overloading the existing lines.

The technique involves first finding a sequence of candidate buses to be compensated using loss sensitivity factors. The optimal size of capacitors is then determined keeping in consideration the worthiness of investment for capacitor placement. Voltage profile is continued to be improved as long as the investment is worthy and line loss is reduced. The proposed technique is tested on IEEE 9 bus, IEEE 15 bus and IEEE 34 bus radial distribution system network with considerations for changing loads. The variable loading condition scenario is implemented considering winter off peak as the minimum loading and summer peak as the maximum loading condition. Comparison with other reported techniques show that the proposed technique obtains a better performance.

This research work is beneficial to different parties both directly and indirectly. The direct beneficiaries of this research work are the distribution companies. This work will help power distribution companies in reducing both real and reactive power losses in their networks.

Furthermore, improvement of the voltage levels at the consumers end will enable the distribution utilities to avoid the costs incurred during compensation of spoilt customer equipment due to voltage deviations outside the acceptable limits. This will make the utilities more economical and reliable in operation.

6.2 Future Scopes of Work

Practical implementation of the capacitor placement technique requires further cost-benefit analysis which in turn depends on the costs of capacitor bank and energy savings. The simulation results can be used to develop a model using any artificial intelligence technique that can accurately calculate the location and size of capacitor for any load conditions. This gives a great promise for practical implementation of the proposed technique.

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Appendix A

IEEE 9 bus distribution network data set

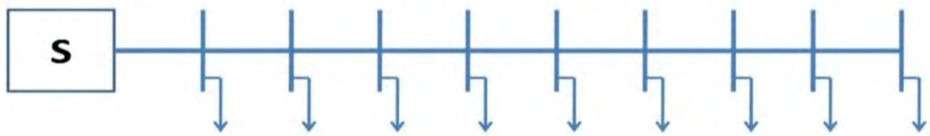

Fig A.1: IEEE 9 bus network

Table A.1: Branch data for IEEE 9 bus network

Line No.	From Bus, i	To Bus, i+1	$R_{i,i+1}$ ohm	$X_{i,i+1}$ ohm	$R_{i,i+1}$ p.u	$X_{i,i+1}$ p.u
1	0	1	0.1233	0.4127	0.023308	0.078015
2	1	2	0.014	0.6057	0.002647	0.114499
3	2	3	0.7463	1.205	0.141078	0.227788
4	3	4	0.6984	0.6084	0.132023	0.115009
5	4	5	1.9831	1.7276	0.374877	0.326578
6	5	6	0.9053	0.7886	0.171134	0.149074
7	6	7	2.0552	1.164	0.388507	0.220038
8	7	8	4.7953	2.716	0.906484	0.513422
9	8	9	5.3434	3.0264	1.01009	0.572098

Table A.2: Load data for IEEE 9 bus network

Bus No.	Summer Peak load		Winter Off-peak Load (assumed to be 60% of summer peak load)	
	P_L, kW	Q_L, kVAr	P_L, kW	Q_L, kVAr
1	1840	460	1104	276
2	980	340	588	204
3	1790	446	1074	268
4	1598	1840	959	1104
5	1610	600	966	360

Bus No.	Summer Peak load		Winter Off-peak Load (assumed to be 60% of summer peak load)	
	P_L, kW	Q_L, kVAr	P_L, kW	Q_L, kVAr
6	780	110	468	66
7	1150	60	690	36
8	980	130	588	78
9	1640	200	984	120
Total	12368	4186	7421	2512

Table A.3: Network design parameter for IEEE 9 bus network

Sl. No.	Description	Unit	Value
1	System Voltage	kV	23
2	System frequency	Hz	50
3	**Bus**		
	Base Voltage	kV	23
	Operating Voltage	kV	23
	No. of Bus		9
	Swing Bus		Bus 0 (B0)
4	**Bus Voltage limit**		
	Mnimum	p.u	0.9
	Maximum	p.u	1.1
5	**Conductor used in the line**		
	Conductor type		Overhead
	Conductor Material		Aluminium
	Conductor Standard Loading Limit	Ampere	600
	Conductor Emmergency Loading Limit	Ampere	720
6	Utility is connected to		Bus 0 (B0)

IEEE 15 bus distribution network data set

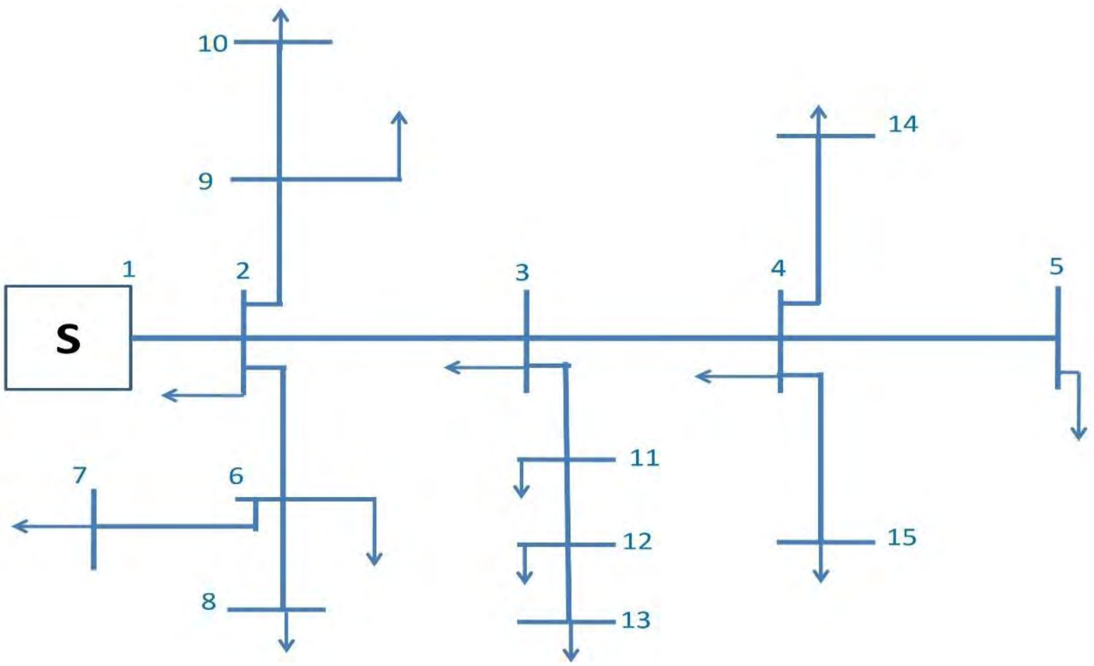

Fig A.2: IEEE 15 Bus distribution network

Table A.4: Branch data for IEEE 15 bus network

Line No.	From Bus, i	To Bus, i+1	$R_{i,i+1}$ ohm	$X_{i,i+1}$ ohm	$R_{i,i+1}$ p.u	$X_{i,i+1}$ p.u
1	1	2	1.3509	1.32349	1.11645	1.09379
2	2	3	1.17024	1.14464	0.96714	0.94598
3	3	4	0.84111	0.82271	0.69513	0.67993
4	4	5	1.52348	1.0276	1.25907	0.84926
5	2	9	2.01317	1.3579	1.66378	1.12223
6	9	10	1.68671	1.1377	1.39398	0.94025
7	2	6	2.55727	1.7249	2.11345	1.42554
8	6	7	1.0882	0.734	0.89934	0.60661
9	6	8	1.25143	0.8441	1.03424	0.6976
10	3	11	1.79553	1.2111	1.48391	1.00091
11	11	12	2.44845	1.6515	2.02351	1.36488
12	12	13	2.01317	1.3579	1.66378	1.12223
13	4	14	2.23081	1.5047	1.84364	1.24355
14	4	15	1.19702	0.8074	0.98927	0.66727

Table A.5: Load data for IEEE 15 bus network

Bus No.	Summer Peak load		Winter Off-peak Load (Assumed to be 60% of summer peak load)	
	P_L, kW	Q_L, kVAr	P_L, kW	Q_L, kVAr
1	0	0	0	0
2	44	45	26	27
3	70	71	42	43
4	140	143	84	86
5	44	45	26	27
6	140	143	84	86
7	140	143	84	86
8	70	71	42	43
9	70	71	42	43
10	44	45	26	27
11	140	143	84	86
12	70	71	42	43
13	44	45	26	27
14	70	71	42	43
15	140	143	84	86
Total	**1226**	**1250**	**734**	**753**

Table A.6: Network design parameter for IEEE 15 bus network

Sl. No.	Description	Unit	Value
1	System Voltage	kV	11
2	System frequency	Hz	50
3	**Bus**		
	Base Voltage	kV	11
	Operating Voltage	kV	11
	No. of Bus		15
	Swing Bus		Bus 1 (B1)
4	**Bus Voltage limit**		
	Mnimum	p.u	0.9
	Maximum	p.u	1.1
5	**Conductor used in the line**		

Sl. No.	Description	Unit	Value
	Conductor type		Overhead
	Conductor Material		Aluminium
	Conductor Standard Loading Limit	Ampere	400
	Conductor Emmergency Loading Limit	Ampere	480
6	Utility is connected to		Bus 1 (B1)

IEEE 34 bus radial distribution network data set

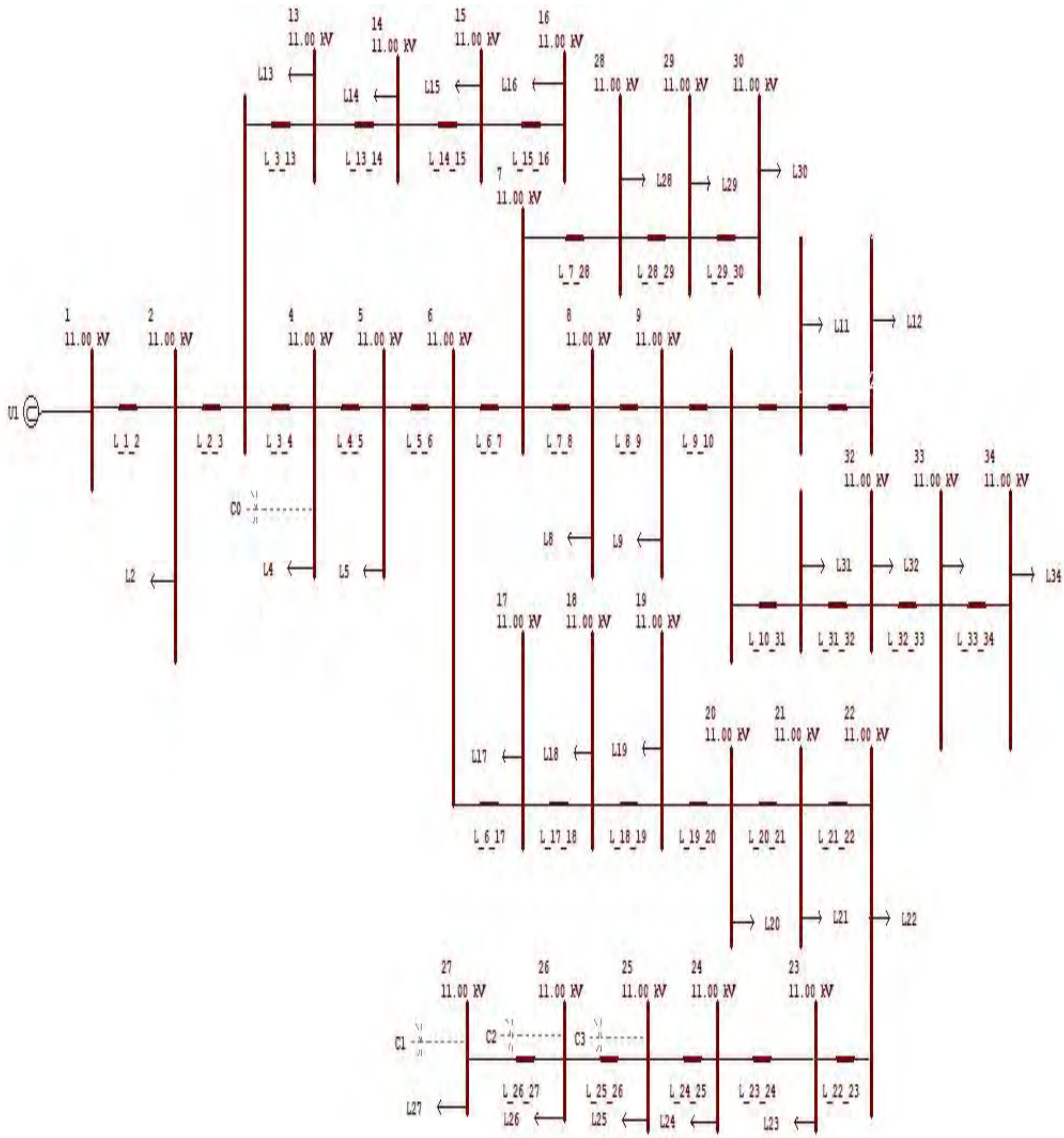

Fig A.3: IEEE 34 bus network

Table A.7: Branch data for IEEE 34 bus network

Line ID	Bus From	Bus To	R_i,i+1 (Ω)	X_i,i+1 (Ω)	R_i,i+1 (p.u)	X_i,i+1 (p.u)	kV Nominal	Length (m)
L_15_16	15	16	0.524	0.09	0.433058	0.0743802	11	0.1
L_25_26	25	26	0.524	0.09	0.433058	0.0743802	11	0.25
L_26_27	26	27	0.524	0.09	0.433058	0.0743802	11	0.2
L_8_9	8	9	0.524	0.09	0.433058	0.0743802	11	0.6
L_13_14	13	14	0.524	0.09	0.433058	0.0743802	11	0.4
L_23_24	23	24	0.524	0.09	0.433058	0.0743802	11	0.6
L_33_34	33	34	0.524	0.09	0.433058	0.0743802	11	0.2
L_7_8	7	8	0.524	0.09	0.433058	0.0743802	11	0.4
L_14_15	14	15	0.524	0.09	0.433058	0.0743802	11	0.2
L_24_25	24	25	0.524	0.09	0.433058	0.0743802	11	0.4
L_7_28	7	28	0.524	0.09	0.433058	0.0743802	11	0.3
L_11_12	11	12	0.524	0.09	0.433058	0.0743802	11	0.2
L_21_22	21	22	0.524	0.09	0.433058	0.0743802	11	0.5
L_31_32	31	32	0.524	0.09	0.433058	0.0743802	11	0.4
L_22_23	22	23	0.524	0.09	0.433058	0.0743802	11	0.5
L_32_33	32	33	0.524	0.09	0.433058	0.0743802	11	0.3
L_10_11	10	11	0.524	0.09	0.433058	0.0743802	11	0.25
L_20_21	20	21	0.378	0.086	0.312397	0.0710744	11	0.5
L_19_20	19	20	0.378	0.086	0.312397	0.0710744	11	0.5
L_10_31	10	31	0.524	0.09	0.433058	0.0743802	11	0.3
L_29_30	29	30	0.524	0.09	0.433058	0.0743802	11	0.3
L_2_3	2	3	0.195	0.08	0.161157	0.0661157	11	0.55
L_3_13	3	13	0.524	0.09	0.433058	0.0743802	11	0.3
L_1_2	1	2	0.195	0.08	0.161157	0.0661157	11	0.6
L_9_10	9	10	0.524	0.09	0.433058	0.0743802	11	0.4
L_6_7	6	7	0.524	0.09	0.433058	0.0743802	11	0.6
L_6_17	6	17	0.298999	0.083	0.247107	0.068595	11	0.6
L_5_6	5	6	0.298999	0.083	0.247107	0.068595	11	0.5
L_4_5	4	5	0.298999	0.083	0.247107	0.068595	11	0.5
L_17_18	17	18	0.298999	0.083	0.247107	0.068595	11	0.55
L_18_19	18	19	0.378	0.086	0.312397	0.0710744	11	0.55
L_28_29	28	29	0.524	0.09	0.433058	0.0743802	11	0.3
L_3_4	3	4	0.298999	0.083	0.247107	0.068595	11	0.55

Table A.8: Load data for IEEE 34 bus network

Bus	Summer peak		Winter off peak (assumed to be 60% of summer peak)	
	P (kW)	Q(kVAr)	P (kW)	Q(kVAr)
1	0	0	0	0
2	230	142.5	138	86
3	0	0	0	0
4	230	142.5	138	86
5	230	142.5	138	86
6	0	0	0	0
7	0	0	0	0
8	230	142.5	138	86
9	230	142.5	138	86
10	0	0	0	0
11	230	142.5	138	86
12	137	84	82	50
13	72	45	43	27
14	72	45	43	27
15	72	45	43	27
16	135	75	81	45
17	230	142.5	138	86
18	230	142.5	138	86
19	230	142.5	138	86
20	230	142.5	138	86
21	230	142.5	138	86
22	230	142.5	138	86
23	230	142.5	138	86
24	230	142.5	138	86
25	230	142.5	138	86
26	230	142.5	138	86
27	137	85	82	51
28	75	48	45	29
29	75	48	45	29
30	75	48	45	29
31	57	34.5	34	21
32	57	34.5	34	21
33	57	34.5	34	21

Bus	Summer peak		Winter off peak (assumed to be 60% of summer peak)	
	P (kW)	**Q(kVAr)**	**P (kW)**	**Q(kVAr)**
34	57	34.5	34	21
Total	4758	2941	**2853**	**1774**

Table A.9: Network design parameter for IEEE 34 bus network

Sl. No.	Description	Unit	Value
1	System Voltage	kV	11
2	System frequency	Hz	50
3	**Bus**		
	Base Voltage	kV	11
	Operating Voltage	kV	11
	No. of Bus		34
	Swing Bus		Bus 1 (B1)
4	**Bus Voltage limit**		
	Mnimum	p.u	0.9
	Maximum	p.u	1.1
5	**Conductor used in the line**		
	Conductor type		Overhead
	Conductor Material		Aluminium
	Conductor Standard Loading Limit	Ampere	400
	Conductor Emmergency Loading Limit	Ampere	480
6	Utility is connected to		Bus 1 (B1)