

2020-03-24

IMPROVING THE PERFORMANCE OF A RADIAL DISTRIBUTION NETWORK USING SHUNT CAPACITORS CASE STUDY IN WOLDIA DISTRIBUTION NETWORK

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SCHOOL OF RESEARCH AND POSTGRADUATE STUDIES

**FACULTY OF ELECTRICAL AND COMPUTER
ENGINEERING**

**IMPROVING THE PERFORMANCE OF A RADIAL DISTRIBUTION
NETWORK USING SHUNT CAPACITORS**

CASE STUDY IN WOLDIA DISTRIBUTION NETWORK

BY ADAMTACHEW ANTENEH MEKONNEN

Bahir Dar, Ethiopia

August 25, 2017

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USING SHUNT CAPACITORS

CASE STUDY IN WOLDIA DISTRIBUTION NETWORK

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A THESIS SUBMITTED TO THE SCHOOL OF RESEARCH AND GRADUATE
STUDIES OF BAHIR DAR INSTITUTE OF TECHNOLOGY, BDU IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER IN
THE POWER SYSTEM ENGINEERING IN THE FACULTY OF ELECTRICAL
AND COMPUTER ENGINEERING

Advisor:

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Bahir Dar, Ethiopia

August 25, 2017

DECLARATION

I, the undersigned, declare that the thesis comprises my own work. In compliance with internationally accepted practices, I have acknowledged and refereed all materials used in this work. I understand that non-adherence to the principles of academic honesty and integrity, misrepresentation/ fabrication of any idea/data/fact/source will constitute sufficient ground for disciplinary action by the University and can also evoke penal action from the sources which have not been properly cited or acknowledged.

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ACKNOWLEDGEMENTS

First of all, I shall praise and thank the Almighty Lord for helping me through this difficult but very inspiring work and for providing me with the ideas and patience necessary for the successful completion of this thesis.

Then, I would like to express my deepest gratitude and appreciation to my supervisors and mentors, Dr.-Ing. Belachew Bantyriga, for his guidance and encouragement through this journey of growth and discovery. His patience and support has enabled me to achieve my highest potential in both academic and professional work. This has been an opportunity of a lifetime for which I am truly thankful.

My sincere thanks is also to Mr. Tesfaye Mohamed Woldia substation EEP employees for his support in obtaining the tools and data necessary for conducting my research and for facilitating my schedule, so that I could meet my commitments. His encouragement and comments are highly appreciated.

Finally, I would like to thank all my friends in Bahir Dar University, specially Mr. Berhanu Zelalem who helped me through the course of my studies, discussed ideas about my research, commented my research and made my life enjoyable.

Thank you all!

ABSTRACT

Capacitors are commonly used in distribution system for reactive power compensation so that it reduces the losses, increases the maximum flow through cables and in transformers, and also improves the system power factor and voltage profile. This thesis presents the way of improving the performance of distribution network by minimizing the reactive current flowing through the distribution networks with optimally allocating shunt capacitors. The optimal shunt capacitor allocation problem is the determination of the location and size of the capacitor to be placed in distribution networks in an optimal manner to reduce the peak power losses of the networks. Single capacitor is connected at each bus and repetitive loss minimization technique is applied to identify the sequence of nodes to be compensated. Optimizing the loss saving equations with respect to the capacitor current for multiple capacitors is used to identify the global capacitor size needed for compensation. To obtain the energy savings, a power flow for radial distribution network is executed using MATLAB programs before and after compensation. The study of this work was conducted on two primary distribution feeders having 82 and 26 buses of woldia distribution networks. Through optimal locating and sizing of shunt capacitors on 82 and 26 buses radial distribution feeders 60.63 % and 33.66 % of the total loss is reduced respectively.

Key words: Distribution systems, Capacitors location and size, Loss reduction.

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LIST OF SYMBOLS AND NOTATIONS

IM	Branch to node incidence matrix
I_a	The active component of branch currents
G^c	$k \times n$ Matrix derived from G
C	$K \times K$ Square matrix
V_i	The line voltage of bus i
I_r	The reactive component of branch currents
P_{la}	The total real power loss due to the active component of branch currents
D	k Dimensional vector
G	Node-to-branch incidence matrix
Q_{ci}	The capacitor required in the i^{th} node
I_{ij}	The current flows from bus i to bus j (the current flows in branch j)
I_{ci}	The i^{th} node capacitor current
Q_{copt}	The global optimum capacitor size
I'_r	The reactive component of branch currents after a single capacitor placement
S_i	The total complex power demand at bus i
P_{lr}	The total real power loss due to the reactive component of branch currents
ΔP_{LS}	The total real power loss savings due to a single capacitor insertion
S_{Loss}	Total power loss in the feeder
P_{TLoss}	Total real power loss
$\Delta P'_{LS}$	Total real power loss savings due to multiple node compensation
P'_{lr}	The total real power loss due to the reactive component of branch currents after a single capacitor is connected in the system
I''_r	The total real power loss due to the reactive component of branch currents after multiple nodes are compensated
K	Number of capacitor buses
n	Number of branches

ABBREVIATIONS

KVA	Kilo volt ampere
Kw	Kilo watt
Kvar	Kilo volt ampere reactive
Kv	Kilo volt
V	volt
MVA	Mega volt ampere
R	resistance
X	Reactance
Zi	Impedance
DGs	Distribution generations
a.c.	alternating current
d.c.	direct current

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1. INTRODUCTION

1.1. Background

Growth in population and industrialization created huge needs for electrical energy. Unfortunately, electricity is not always used in the same place that it is produced, meaning long-distance transmission lines and distribution systems are necessary. Hence, transmission and distribution lines are vital links between generating stations and consumers as power from generating stations is transmitted at high voltage over long distance to the major load centres and then the power is distributed to various substations located at various places and localities through distribution lines.

At power station, electric power is generated in the range of 11 KV to 25 KV, which is increased by stepped up transformers to the main transmission voltage. At substation, the connections between various components are made, for example, lines and transformers and switching of these components is carried out. Transmission level voltages are in the range of 66 KV to 400 KV (or higher). Large amount of power is transmitted from the generating stations to the load centres at 220KV or higher. In USA, it is at 345 KV, 500 KV and 765 KV and in Britain, it is at 275 KV and 400 KV. The network formed by these very high voltage lines is sometimes called as the super grid. This grid, in turn, feeds a sub-transmission network operating at 132 KV or less[1]. In Ethiopia, networks operate at 400 KV, 230 KV, 132 KV, 66 KV and 45 KV high voltage transmissions, while the medium voltage distribution is in 33KV and 15 KV supplying the final consumer feeders at 380 volt three phase, giving 220 volt per phase.

The primary transmission lines transmit electrical power from step up substations to primary (receiving) stations where voltage is stepped down to sub-transmission voltage level by means of step-down transformers. Power transmitting is extended through sub-transmission lines at the medium voltage levels specified up to the point of main load centres. Any transmission and distribution line possesses resistance, inductance, capacitance and leakage conductance which are distributed along the lines and their magnitudes depend on the length of the line and transmission voltage level. These parameters determine the electrical characteristics of the lines and are essential for the development of the transmission and distribution line models used in power system analysis.

Electricity supply companies are trying to limit the losses in energy in overhead transmission lines to about 2.5%, between the power plant and the step-down substation. The total transmission system loss ranges from 3% to 5% of total power injected to the nodes including losses in the transformers. Between the step-down substation and users, the losses can be about the same or even greater. Therefore, the overall loss between the power plant and users can easily be estimated to be between 8% and 15%, but still there is some room to improve efficiency in the transmission/distribution systems[2].

In our case distribution networks are characterized by radial, long distance, and poor reactive compensation, some of which may risk total or partial collapse in the event of major disturbances and experience low voltage under heavy load. There is also a high customer's turnout in Ethiopia incorporating hundreds of thousands of customers connected to the existing system even excluding the additions due to rural electrification-planned transmission system expansion is under fast implementation at present, thus more customers are going to be connected to the existing (old) network; this may lead to over loading and high-power loss in some of the lines and system equipment's and consequently reduces system efficiency, degrading voltage profile and reliability. This hypothetical image initiated the researcher to focus on and know present status of the existing distribution network through evaluation of technical loss and adequacy of 15 KV distribution line of length 73.673 and 15.07 km from Woldia substation.

A typical distribution system consists of a step-down transformer at a bulk supply point feeding a number of lines with varying length from a few hundred meters to several kilometres. Several three phase step-down transformers, e.g. 15KV/380V are spaced along the feeders and from these, three phases four wire networks of consumers are supplied which give 220-volt single phase supply to houses and similar loads.

Nowadays, it is acknowledged that the reduction of losses especially in the distribution networks, leads to power and energy cheaper than building new capacities of production and transmission. Energy efficiency is accepted by the specialists as the most available, the least pollutant and cheapest resource of all. In order to explain this, it was proved that 1 installed KW is four times more expensive than 1 saved KW.

In practice, energy transfer efficiency reduced due to the phase shift between voltage and current at the fundamental frequency. The phase shift arises largely due to energy flows characterizing electric motors that dominate the aggregated load.

Reactive currents in an electric utility distribution system produce losses and result in increased ratings for distribution components. Shunt capacitors are commonly used in distribution systems for several reasons, in particular in order to reduce power losses, to improve the voltage profile along the feeders and to reduce the maximum flow through cables and transformers. These benefits depend greatly on how capacitors are placed in the system. The general capacitor placement problem is how to optimally determine the locations to install capacitors and sizes of capacitors to be installed in the buses of radial distribution systems.

1.2. Motivation

It is well known that there are an all-round energy crises all over the world and efforts are being made to conserve energy during the stages of conversion, transmission, distribution and at end use equipment. Studies have showed that reduction of losses in the power networks is much more beneficial than the increase of generating capacities. Distribution networks are well known for their high R/X ratio and significant voltage drop that could causes substantial power losses along the feeders. It is estimated that 13 % of the total power generation is lost in the distribution networks [2]. Portion of this loss is caused by the reactive current flowing in the network.

Reactive currents in an electrical utility distribution system produce losses, result in increased ratings for distribution components, reduced system voltage and capacities. As the industrial and overall economy of the country grows, the electrical energy demand increases proportionally. To fill the gap between energy demand and supply, the country has to go for both additional power generation and improving the performance at both utility and consumer sides. In This thesis based on our knowledge about the importance of loss reduction on distribution networks both the utility and consumers side are improve its performance utilization of power.

1.3. Problem Description

In context of economic activities increasing in recent years in Ethiopia, results in rapid growth in electrical demand, especially in commercial and industrial sectors. Most of the electrical equipment connected to a power supply are industrial and commercial loads and delivery apparatus are inductive in nature and therefore operate at lower power factor angles. Therefore, the power system operating in high reactive current

Thus, due to a high supplied reactive current in distribution networks results in:

- High I^2R loss in distribution networks.
- Reduced the system capacity to supply the load demand.
- the system voltage at the load end is below the standard.
- Operating in under voltage condition result in failure of equipment's.

1.4. Objectives

The objective of this thesis reduces the loss in distribution networks by placing the optimal capacitors size and location of proper place in order to improve the performance of a radial distribution network power delivery.

The general and specific objectives of the thesis are:

- General Objective

The general objective of this thesis is to study and analyse woldia distribution network to improve its performance and to develop recommendations to satisfy the increased demand of power.

- Specific Objectives

The specific objectives of this thesis are by select feeder line noted as follows

- Identify the optimal location of the capacitors.
- Select the size of capacitor needed.
- Make conclusion and recommendation for implementation is to be measurable.

1.5. Study Area

This research is conducted in Amhara regional state in woldia town. woldia town is selected for the study area for the following reasons.

- There is fast demand growth in industrial, agriculture and commercial sectors the industrial, agriculture and commercial loads and delivery apparatus are inductive in nature which results high reactive current flows.
- It is distant from generation station and vulnerable to high voltage drop in transmission line.
- Having long distance distribution line.
- There is no study conducted before to reduce loss in distribution networks.
- Measures taken to reduce reactive power flow from the generation by supplying it near to the load side using capacitors are less.

Even though this research is conducted at woldia town, through modifying the line and load data according to the configuration of the feeder, can be possible implemented in any distribution networks where there are much reactive power flow and a considerable feeder length. Woldia town is in Amhara region which is situated 521 km away in Northern direction from the capital city of Ethiopia (Addis Ababa). The map of study area is shown in Figure 1-1

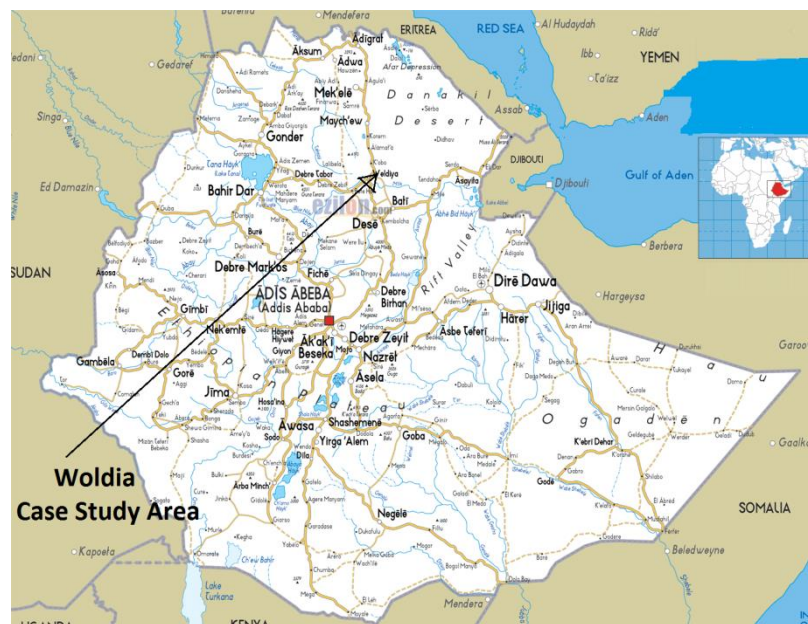


Figure 1-1 Map of study area

Woldia town is first electrified in the year 1982 E.C from woldia substation. Woldia substation which has an installed capacity of 17 MVA (1x8.4 MVA, 1x6.3 MVA and 1x3 MVA) and it receives 66 KV from Chombolch substation (having capacity of 40 MVA) in parallel to Dessie substation (having capacity of 34 MVA) through 80 km long ACSR-70 conductor.

There are three step-down power transformers in this substation, the first transformer steps down 66KV to 33KV and 15KV for primary distribution. The second and third transformer steps down 66KV to 15KV. From the first transformer four feeders are emanated, they are named as: Shunta, Chefera, Woldia-II and Mechara. Similarly, the second transformer tow feeders are emanated, they are named as: Woldia-I and Gobeye and third transformer one feeder are emanated, they are named as: Wochale. From the total feeders three of them are used to distribute power to the town and near village, the rest four (i.e. Shunta, Chefera, Gobeyeand Wochale) go to nearby small towns as shown in single line diagram on Figure 1-2.

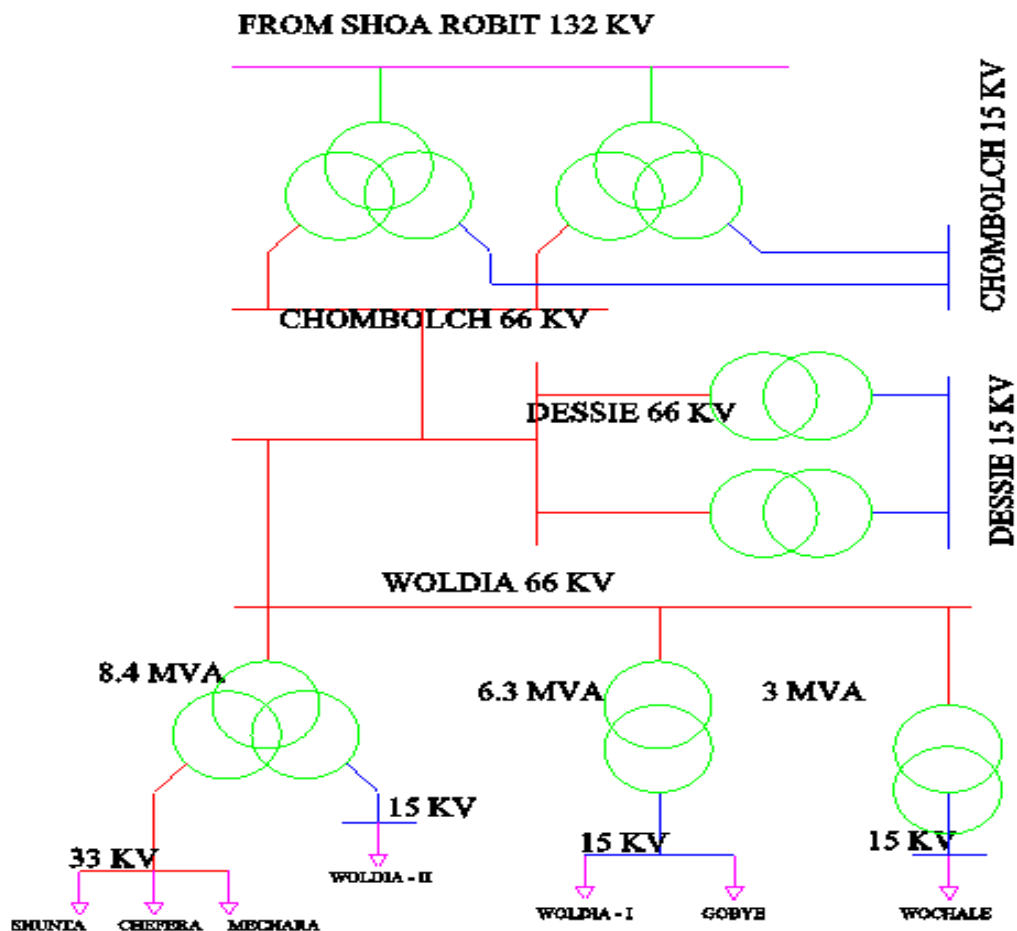


Figure 1-2 Single line diagram of the study area

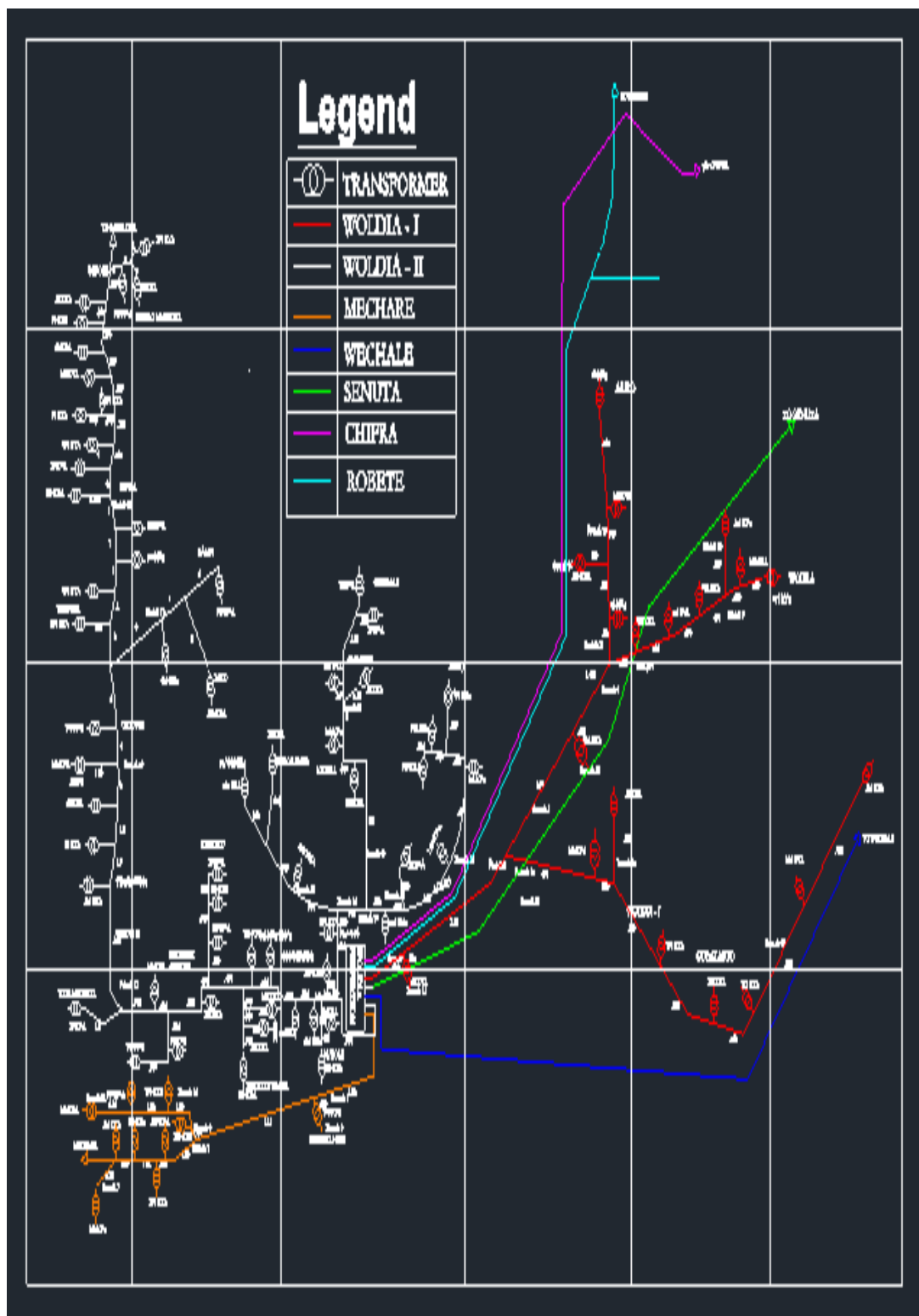


Figure 1-3 Radial configured feeder line of Woldia town

The feeders in the town are configured radially as shown in Figure 1-3 with voltage level of 33 KV and 15 KV. The primary feeders are connected to a total of more than 370 distribution power transformer and most of them are pole mounted.

For the study of this thesis two feeders are selected ('Woldia I, and Woldia-II). Because these feeders:

- Have larger demand at the substation.
- Having long distance radial distribution line.
- Incorporate all kind of loads (industrial, commercial and domestic loads).

2. LITRATUREREVIEW

The connection of autonomous power sources at optimum sizing and locations along radial distribution feeders is previously carried out with shunt power capacitors. Many approaches have been developed and applied using different modeling and optimization techniques. The potential optimization objectives specifically targeted were minimization of peak power and energy losses increasing of installed capacity, control of power factor, and improvement of voltage profile. The optimization objectives are usually placed subject to the cost of installed units, statutory levels of voltage profile and ampacity of wire conductors.

This chapter reviews a set of previous work dealing with the theories and studies of optimal sizing and location of shunt capacitors on radial distribution feeders.

2.1. Optimal Sizing and Location of Shunt Capacitors in different Technique

In June, 2009 K. Bansal, in his paper 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 on 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 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 minimizing the loss associated with the reactive component of branch currents by placing shunt capacitor. 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 equation with respect to the capacitor currents. The performance of the proposed method was investigated on distribution systems consisting of 28 buses and it was found that a significant loss saving can be achieved by placing optimal capacitors in the system [15].

In April 2001 L.Holdsworth, presented in his paper for many years, it was generally understood that a.c. transmission systems could not be controlled fast enough to handle dynamic system conditions, the dynamic system problems were usually handled by over-design, which resulted in underutilisation of the system.

Flexible AC Transmission System (FACTS) devices play an important role in improving the dynamic performance of power system and hence achieve better utilisation of the available system. they are principally employed to rapidly control one or more of the three main parameters directly affecting a.c. power transmission, namely the system impedance, magnitude and phase angle of the system voltage. The voltage source inverter is the basic building block of most FACTS device [3].

L.Ramesh and et.al presented accurate loss minimization is the critical component for efficient electrical distribution power flow. The contribution of this work presents loss minimization in power distribution system through feeder restructuring, incorporating DG and placement of capacitor [11].

In A. Yadav and et.al discussed in distribution system is the major link which provides supply to the consumers from the high voltage transmission system. The load on the distribution system is not constant and it changes with respect to time throughout the working period. The voltage drops and power losses occur in the distribution system mainly depends on the nature of the load which is applied on the system. The voltage drops and power losses frequently occurs mainly on those systems which are supplying load to the industrial areas, this is mainly because of the existence of more reactive power. To overcome these problems shunt compensation is employed to reduce or suppress those effects to an extent. The aim of this is to determine the specific value of the shunt capacitance required to achieve the permissible voltage tolerance limits and maximum percentage of power loss reduction in a sample two feeder radial distribution system [14].

In December 2013Shashikanth and et.al presented the approach for optimal placement of hybrid system consists of capacitor banks and STATCOM in a real power network for the purpose of economic enhancement of voltage and load relief. The optimization problem is solved by the use of MATLAB simulation. As a result, the size and proper location of capacitors and STATCOM are determined.

By applying the proposed method, the economic costs and power losses are reduced to a considerable extent while enhancing the voltage profile and decreasing load current [21].

G. Krishnan and et.al energy losses occur in the process of supplying electricity to consumers due to technical and commercial losses. In his paper, the technical losses are due to energy dissipated in the conductors and equipment used for transmission, transformation, sub transmission and distribution of power.

These technical losses are inherent in a system and can be reduced to an optimum level. A study on technical losses in distribution system and analysis of the impact of losses in power sector. The technical losses caused by material properties and its resistance to the flow of electrical current in distribution system will be analysed and simulated through electrical transient analysis program. Moreover, the impact of different types of transformer and other equipment's connections to the substation and feeder will also be investigated [17].

M. Legha and et.al presented that increasing application of capacitor banks on distribution networks are the direct impact of development of technology and the energy disasters that the world is encountering. To obtain these goals the resources capacity and the installation place are of a crucial importance. In this paper, a new method is proposed to find the optimal and simultaneous place and capacity of these resources to reduce losses, improve voltage profile. The advantage of ABC algorithm is that it does not require external parameters such as cross over rate and mutation rate as in case of genetic algorithm and differential evolution and it is hard to determine these parameters in prior [17].

N. Acharya and et.al this thesis presents various facts related to the landmark development: practical installations, benefits and application of FACTS controllers in the electric utilities. The history of development of these devices is presented along with the information regarding the first utility installation/demonstration of FACTS devices. A comprehensive collection of major FACTS installations around the world is then presented. The paper also analyses the benefit that can be achieved and cost associated with these devices.

The thesis also presents various applications that FACTS devices can have in the deregulated market. Various issues related with the FACTS controllers are also presented. The problem of high losses of advanced FACTS controllers as compared to conventional counterpart and need to take into account of interaction among controllers in future power system is highlighted [18].

S.Singh and et.al proposed technique to solve the optimal placement and sizing problem of fixed capacitor banks in distributed power networks in smart grid environment. The objective is to monitor and regulate the network voltage centrally, regarding the overall voltage profile or improvement of overall power factor in the power system for the construction process of Thermal Power Plant. Thus, it is essential to build a database that provides the optimal location and sizing of capacitor units for different loading conditions. This database can be used in a subsequently steps for construction power network using power factors of various machines & motors. Uses of various algorithm makes it time taking process with tedious work. So, with the help of some commonly known factors sizing can be done [22].

In M. Karimi and et.al Shunt capacitors are commonly used in distribution system for reactive power compensation. In his paper compare different analytical, numerical programming, heuristic and artificial intelligent based techniques have been proposed in the literature for optimum shunt capacitor bank placement. This paper will present a very detailed overview of optimum shunt capacitor bank placement techniques. Six different approaches of optimum shunt capacitor bank placement based on minimization of power losses, weakest voltage bus approach and maximization of system loadability will be applied on four different radial distribution test systems. The results will be compared on the basis of power loss reduction, voltage profile improvement, system loadability maximization and the line limit constraint [16].

M. Sedighzadeh and et.al presented new optimal reconfiguration and capacitor placement are used to reduce power losses and keep the voltage within its allowable interval in power distribution systems considering voltage, current, and radial condition constraints. It is needed to solve two nonlinear discrete optimization problems simultaneously, so an intelligent algorithm is used to reach an optimum solution for network power losses.

An effective method and a new optimization algorithm using 'improved binary Particle Swarm Optimization' is presented and discussed to minimize power losses in distribution network by simultaneous network reconfiguration and capacitor placement. The proposed model uses binary strings which represent the state of the network switches and capacitors. The algorithm is applied in systems to find the optimum configuration of the network with regard to power losses. Five different cases are considered, and the effectiveness of the proposed technique is also demonstrated with improvements in power loss reduction compared to other previously researched methods, through MATLAB under steady-state conditions [20].

G. Harisha and et.al in his paper Capacitors and DGs are commonly used in distribution system for real or reactive power compensation so that it reduces the losses, increases the maximum flow through cables and in transformers, and also improves the system power factor and voltage profile. The Reduction of losses in distribution system is very essential to improve overall efficiency of power delivery. This can be achieved by placing capacitors and DGs at different locations in radial distribution system. By considering the above advantages, in this paper to improve voltage profile and to reduce losses to increase efficiency in radial distribution system, the location and sizing of capacitors and DGs are addressed using two main factors.

They are loss sensitivity factor for location and particle swarm optimization algorithm for sizing is used. To show the effectiveness, obtained results are compared each other. The proposed method is programmed and tested in distribution system using MATLAB software. For load flow analysis of the distribution network, Newton-Raphson method is used [2].

G.Ibe and et.al the intent of this paper is to present an analysis of reactive power control and voltage stability in power systems. It identifies a new model used to enhance voltage stability and exposes several key issues that had remained as research challenges in this area. The steady state voltage and reactive power control in distribution systems can be properly controlled by coordinating the available voltage and reactive power control equipment, such as on-load tap-changers, substation shunt capacitors and feeder shunt capacitors. It began with an overview of reactive power and voltage stability in transmission, distribution and load, and the importance of providing reactive power locally.

The description of selected control features of shunt power systems such as SVC (Static Var Compensator), static compensators of reactive power, STATCOM-type systems (Static Compensator), static reactive power generators and systems that combine both these solutions, which are referred to as SVC based on STATCOM were not left out. It explains the need to improve the voltage stability of Power system, as well as the increasing requirements for energy quality and security. It also discusses the techniques that were adopted in controlling and monitoring of the rate of power flow in the entire power system topology. This investigates the system to an optimal level in order to reduce losses and ensures sufficiency of reactive power control during normal and emergency conditions and to prevent voltage collapse [5].

K. Sharma and et.al This paper presents various techniques to reduce these losses and their contribution in improving power efficiency of distribution system. An electric distribution system plays an important role in achieving satisfactory power supply. The quality of power is measured by voltage stability and profile of voltage. But because of losses in distribution system, its voltage profile affects. Basically, the losses could be defined as the difference between the metered unit's energy input into the distribution system and the total energy paid that leaving the network through electricity accounts, whether calculated or estimated, in any given period. As, total distribution losses equals to sum of technical losses and non-technical losses [9].

P. Iyappan and et.al Here in his project different generators such as wind, thermal, hydro stations are being connected to the system in which the loads are also connected to that bus system. the power generated is usually delivered to the load terminals. But large amount of power is wasted in the form of heat, line losses. In order to balance the sending end power and receiving end power svc is used to overcome the losses. Thus, svc should be added at the dynamic position to improve the bus voltage. When the loads are on, the voltage gets dipped at the particular bus. So, in that bus the svc should be added to improve the bus voltage. By, this voltage sag, and harmonics can be reduced [19].

M. Legha and et.al Increasing application of capacitor banks on distribution networks is the direct impact of development of technology and the energy disasters that the world is encountering. To obtain these goals the resources capacity and the installation place are of a crucial importance.

In this paper, a new method is proposed to find the optimal and simultaneous place and capacity of these resources to reduce losses, improve voltage profile. The advantage of ABC algorithm is that it does not require external parameters such as cross over rate and mutation rate as in case of genetic algorithm and differential evolution and it is hard to determine these parameters in prior [12].

K. Tilakul and et.al in this paper presents the capacitor bank location and size to reduce the total power losses and its cost by optimizing location and size of the capacitor bank in the distribution feeder in Lao PDR. The voltage drop and power loss before and after installing the capacitor were compared in this work. The result showed better voltage profiles and power losses of the distribution system could be improved by using the proposed method with 9 and 37-buses in Vientiane province. The proposed method can be a benefit in the distribution feeder analysis for planning and operation in Lao PDR [10].

D. Sharma and et.al Capacitors in power systems are generally used to supply reactive power to reduces losses and improvement of the voltage profile. The appropriate placement of capacitors is also important to ensure that system power losses and total capacitor costs can be reduced. This paper presents a new constraint objective cost function to maximize the net annual savings by minimizing real power loss and optimizing the purchase cost of shunt capacitors while maintaining a better node voltage profile of the system. Here two steps solution methodology i.e.loss sensitivity factors for identification of candidate buses to place the capacitors and real coded genetic algorithm to determine the value of optimal capacitor have been adopted. The effectiveness of the proposed method has been tested. Result shows that after placement of capacitor in candidate buses the energy loss has been reduced [8].

3. THEORETICAL BACKGROUND FOR DISTRIBUTION SYSTEM

3.1. Introduction

An electric supply system consists of three principal components. That is, the power station, the transmission lines and the distribution system. Electric power is produced at the power stations which are located at suitable places, generally away from the customers. It is then transmitted over large distances to load centres with the help of conductors known as transmission lines. Finally, it is distributed to a large number of small and big consumers through a distribution network.

The electrical energy produced at the generating station is conveyed to the consumers through a network of transmission and distribution systems. That part of power systems which distributes electric power for local use is known as distribution system. In general, the distribution system is the electrical system between the substation fed by the transmission system and the consumer meters. It generally consists of feeders, distributors and the service mains. Figure 3-1 shows the single diagram of a typical low-tension distribution system.

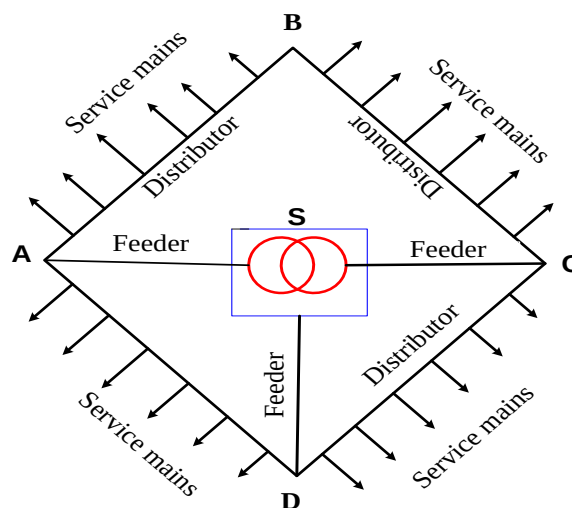


Figure 3-1 Single line diagram of a typical low-tension distribution system

3.1.1. Feeders.

A feeder is a conductor, which connects the substation (or localized generating station) to the area where power is to be distributed. Generally, no tapping are taken from a feeder so that currents in it remain the same throughout.

3.1.2. Distributors.

A distributor is a conductor from which tapping are taken for supply to the consumers. In Figure 3-1 AB, BC, CD and DA are the distributors. The current through a distributor is not constant because tapping are taken at various place along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variation is + 6% of the rated value at the consumer's terminals [23].

3.1.3. Service Mains.

A service main is generally a small cable which connects the distributor to the consumer's terminal.

3.2. Classification of Distribution Systems

A distribution system may be classified according to:

3.2.1. Nature of Current

According to nature of current distribution system may be further classified as Direct current (D.C) distribution system and Alternating current (A.C) distribution system. Now a-days a.c. system is universally adopted for distribution of electric power as it is simpler and more economical than direct current method.

3.2.2. Types of Construction

According to type of construction distribution system may be further classified as overhead system and underground system.

The overhead system is generally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the underground system is used at places where overhead construction is impracticable or prohibited by the local law [4].

3.2.3. Scheme of Connection

According to scheme of connection the distribution system may be classified as radial, ring main system and interconnected system. Each scheme has its own advantages and disadvantages and those are discussed in section 3.4.

3.3. Alternating Current Distribution

Nowadays electrical energy is generated, transmitted and distributed in the form of alternating current. One important reason for the wide spread use of alternating current in preference to direct current is the fact that alternating voltage can be conveniently changed in magnitude by means of a transformer. The a.c. distribution system is classified in to primary distribution system and secondary distribution system, which are described briefly hereunder.

3.3.1. Primary Distribution System

Electrical power from the generating station is transmitted at high voltage to the substation located in or near the city. The transmission system voltage is stepped down to lower levels by distribution substation transformers. The primary distribution system, which is the concern of this paper, that portion of the power network between the distribution substation and the utilization transformers.

It is a part of a.c. distribution system which operates at voltages somewhat higher than general utilization and handles large blocks of electrical energy than the average low voltage consumer uses. The voltage used for primary distribution depends up on the amount power to be conveyed and the distance of the substation required to be fed.

The most commonly used distribution voltages are usually in the range of 4 to 34.5 KV. The primary distribution voltages used by Ethiopian Electric power corporation are 33 and 15 KV. Due to economic considerations, primary distribution is carried out by 3-phase, 3-wire system.

3.3.2. Secondary Distribution System

it is a part of ac distribution system which includes the range of voltages at which the ultimate consumer utilises the electrical energy delivered to them. The secondary distribution employs 380/220V, 3-phase, 4-wire system. The primary distribution circuit delivers power to various substations, called distribution substations. The substations are situated near the consumer's localities and contain step down transformers. At each distribution substation, the voltage is stepped down to 380/220V and power is delivered by 3- phase, 4-wire ac. system.

3.4. Connection Schemes of Distribution System

3.4.1. Radial System

In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Figure 3-2 a and 3-2 b shows a single line diagram of a radial system for d.c and a.c distribution respectively.

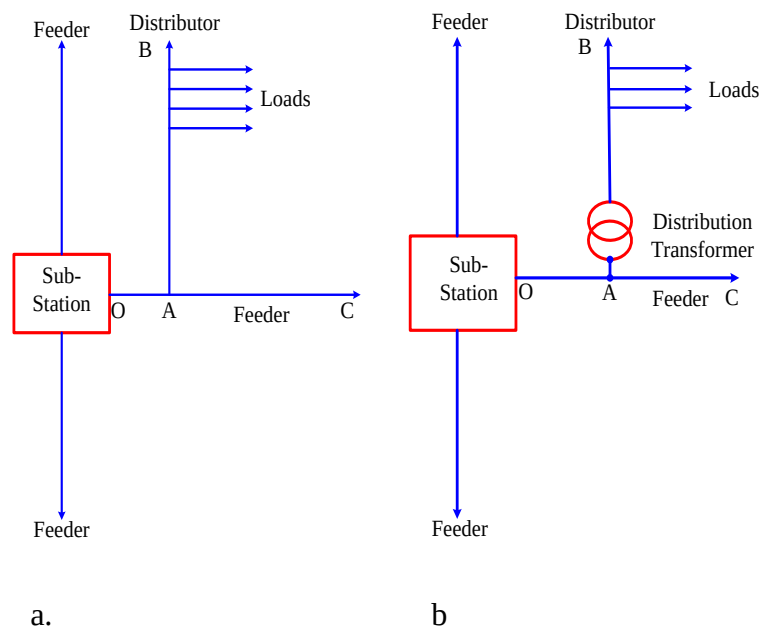


Figure 3-2 Radial distribution systems

This is the simplest distribution circuit and has the lowest initial cost. However, it suffers from the following drawbacks

- The end of the distributors nearest to the feeder point will be heavily loaded
- The customers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder distributor cuts off supply to the customers who are on the side of the fault away from the substation
- The customers at the distant end of the distribution would be subjected to serious voltage fluctuations when the load on the distributor changed.

3.4.2. Ring system

In this system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation. Figure 3-3 shows the single line diagram of ring main system for a.c. distribution where substation supplies to the closed feeder LMNOPQRS. The distributors are tapped from different points M, O, and Q of the feeder through distribution transformers.

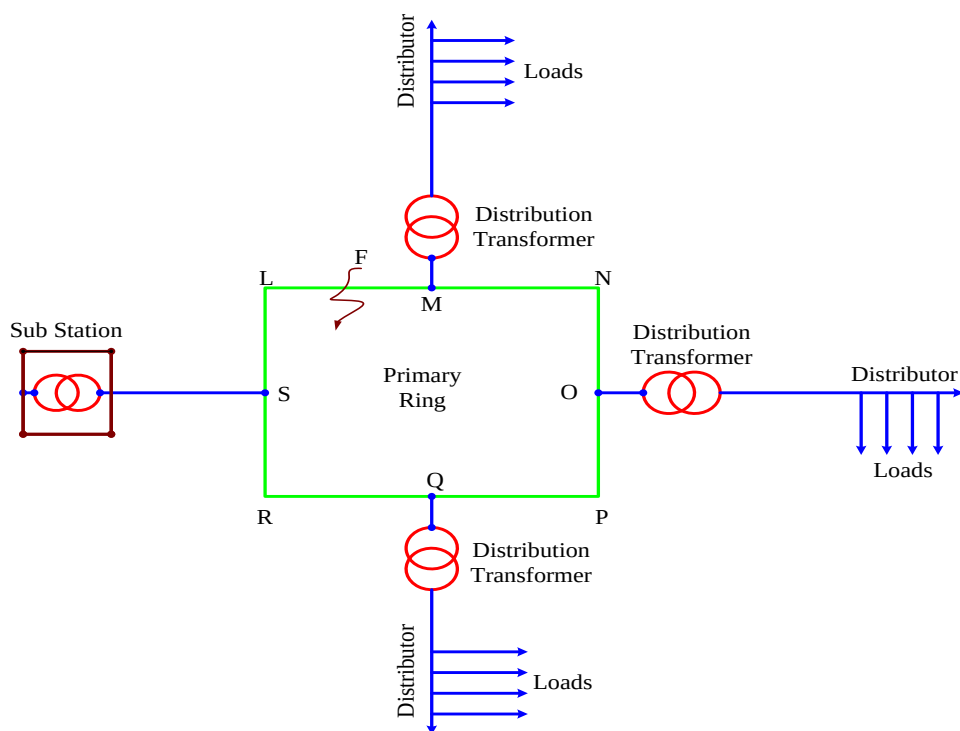


Figure 3-3 Ring main systems

The ring main system has the following advantages:

- There are less voltage fluctuations at consumers terminals
- The system is very reliable as each distributor is fed via two feeders. In the event of fault on any section of feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the customers via the feeder SRQPONM.

3.4.3. Inter Connected System

When the feeder ring is energized by two or more than two generating stations or substations, it is called inter connected system. Figure 3-4 shows a single line diagram of inter connected system where the closed feeder ring ABCD is supplied by two substations S1 and S2 at point D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers.

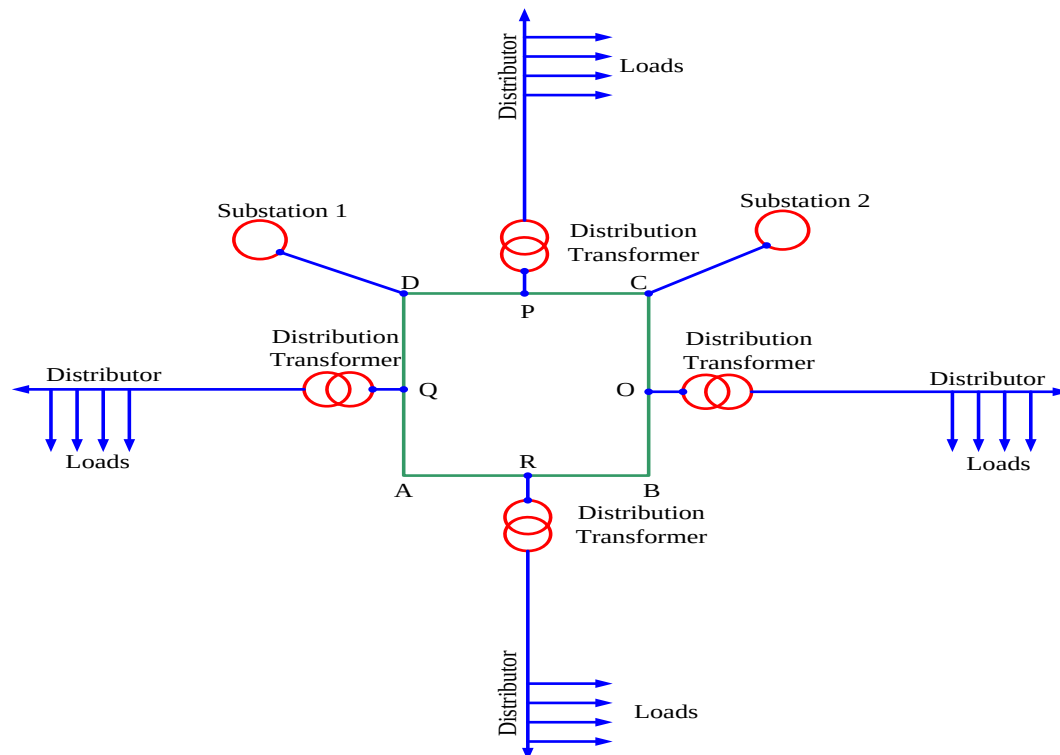


Figure 3-4 Inter connected system

The inter-connected system has the following advantages:

- It increases the service reliability
- Any area fed from one generating station during peak load hours can be fed from the other generating station. This reduces reserve power capacity and increase efficiency of the system

3.5. Line Impedance of a Distribution System

Overhead lines have resistance and reactance that impedes the flow of current. These impedance values are necessary for voltage drop, power flow, short circuit, and line loss calculations.

Depending up on the degree of accuracy required, impedances can be calculated using Carson's equations where no assumptions are made, or the impedances can be determined from tables where a wide variety of assumptions are made [24].

3.5.1. Series Impedances of Overhead Lines

The series impedance of a single phase, two phases (V-phase), or three phase distribution line consists of the resistance of the conductors and the self and mutual inductive reactance resulting from the magnetic fields surrounding the conductors. The inductive reactance (self and mutual) components of the impedance are a function of the total magnetic fields surrounding a conductor.

The series impedance per phase of a transposed three phase line of conductors a, b, c, is given by:

$$z_i = r_i + j0.062832 \ln \frac{D_{eq}}{GMR_i} \Omega/\text{km} \quad 3-1$$

Where r_i =conductor resistance in Ω/km

$$D_{eq} = \sqrt[3]{D_{ab} \cdot D_{bc} \cdot D_{ca}} \text{ meters}$$

GMR_i -geometric mean radius of conductor i in meter

For a solid, round, nonmagnetic conductors, the relationship between the actual radius

and the GMR is: $\frac{GMR}{r} = e^{\frac{-1}{4}}$

For stranded conductors, the GMR is given by:

$$GMR = l.r$$

3-2

Where l = the GMR factor which is given in Table 3-1

r = actual conductor radius

Table 3-1 Geometric mean radius factor

Strands	GMR factor, l
1 (solid)	0.7788
3	0.6778
7	0.7256
19	0.7577
37	0.7678
61	0.7722

Source: Aluminium Association, Ampacities for Aluminium and ACSR overhead electrical conductors, 1986

When distribution systems consist of single phase, two phases and untransposed three phase lines serving un balanced loads, it is necessary to retain the identity of the self and mutual impedance terms of the conductors, and take into account the ground return path for the unbalanced currents. The inductive reactance will be assumed to be at a frequency of 50Hz, and the length of the conductor will be assumed to be one kilometre, with these assumptions the self and mutual impedances are given by:

$$z_{ii} = r_i + j0.062832 \ln \frac{1}{GMR_i} \Omega/\text{km} \quad 3-3$$

$$z_{ij} = j0.062832 \ln \frac{1}{D_{ij}} \Omega/\text{km} \quad 3-4$$

Where

z_{ii} = self-impedance of conductor i in Ω/km

z_{ij} = mutual impedance between conductors i and j in Ω/km

r_i = resistance of conductor i in Ω/km

D_{ij} = distance between conductors i and j in meter

3.5.2. Carson's Equations

Carson made use of conductor images that is every conductor at a given distance above ground has an image conductor the same distance below ground.

The modified Carson's equations will be used to compute the primitive self and mutual impedances of overhead and underground lines which are given by (the derivations are given in appendix A):

$$z_{ii} = r_i + 0.049348 + j0.062832 \left(\ln \frac{1}{GMR_i} + 6.837026 \right) \Omega / \text{km} \quad 3-5$$

$$z_{ij} = 0.049348 + j0.062832 \left(\ln \frac{1}{D_{ij}} + 6.837026 \right) \Omega / \text{km} \quad 3-6$$

Equations 3-5 and 3-6 are used to compute the elements of a n conductor by n conductor primitive impedance matrix.

An overhead four wire ground Wye distribution line segment will result in a 4×4 matrix. For an underground grounded Wye line segment consists of three concentric neutral cables, the resulting matrix will be 6×6 . The primitive impedance matrix for a three phase line with m neutral will be of the form

$$\left[Z_{\text{primitive}} \right] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} & \vdots & Z_{an1} & Z_{an2} & Z_{anm} \\ Z_{ba} & Z_{bb} & Z_{bc} & \vdots & Z_{bn1} & Z_{bn2} & Z_{bnm} \\ Z_{ca} & Z_{cb} & Z_{cc} & \vdots & Z_{cn1} & Z_{cn2} & Z_{cnm} \\ \dots & \dots & \dots & \vdots & \dots & \dots & \dots \\ Z_{n1a} & Z_{n1b} & Z_{n1c} & \vdots & Z_{n1n1} & Z_{n1n2} & Z_{n1nm} \\ Z_{n2a} & Z_{n2b} & Z_{n2c} & \vdots & Z_{n2n1} & Z_{n2n2} & Z_{n2nm} \\ Z_{nma} & Z_{nmb} & Z_{nmc} & \vdots & Z_{nmn1} & Z_{nmn2} & Z_{nmnm} \end{bmatrix} \quad 3-7$$

The phase impedance matrix is given by:

$$\left[\hat{Z}_{abc} \right] = \left[\hat{Z}_{ij} \right] - \left[\hat{Z}_{in} \right] \left[\hat{Z}_{nn} \right]^{-1} \left[\hat{Z}_{nj} \right] \quad 3-8$$

Equation 3-8 is the final form of the kron reduction techniques. The final phase impedance matrix becomes:

$$[Z_{abc}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \Omega / km \quad 3-9$$

The phase impedance matrix for a three-wire delta line is determined by the application of Carson's equations without the kron reduction step.

3.5.3. Sequence Impedances

Many times, the analysis of a feeder will use only the positive and zero sequence impedances for the line segment.

If a line is assumed to be transposed, the phase impedance matrix is modified so the three diagonal terms are equal and all of the off-diagonal terms are equal. When this is done the self and mutual impedances are defined as:

$$z_s = \frac{1}{3}(z_{aa} + z_{bb} + z_{cc}) \Omega / km \quad 3-10$$

$$z_m = \frac{1}{3}(z_{ab} + z_{bc} + z_{ca}) \Omega / km \quad 3-11$$

The sequence impedances can be determined directly as:

$$z_{00} = z_s + 2.z_m \quad \Omega / km \quad 3-12$$

$$z_{11} = z_{22} = z_s - z_m \quad \Omega / km \quad 3-13$$

Where z_{00} and z_{11} are zero and positive sequence impedances

3.6. Requirements of a distribution system

A considerable amount of efforts is necessary to maintain an electric power supply within the requirements of various types of customers. Some of the requirements of a good distribution system are: proper voltage, availability of power on demand and reliability.

3.6.1. Proper Voltage

One important requirement of a distribution system is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumer's terminals are within permissible limits.

The statutory limit of voltage variations is +10% of the rated value at the consumer's terminals. Thus, if the declared voltage is 220 V, then the highest voltage of the consumer should not exceed 233 V while the lowest voltage of the consumer should not be less than 207 V.

3.6.2. Availability of Power on Demand

Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers. This necessitates that operating staff must continuously study load patterns to predict in advance those major load changes that follow the known schedules.

3.6.3. Reliability

Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This calls for reliable service. Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by

- inter connected system
- reliable automatic control system
- providing additional reserve facilities.

3.7. Power Flow Analysis

Power flow analysis is a very important and basic tool for the analysis of any power system as it is used in the planning and design stages as well as during the operational stages. It deals with the calculation of the network operating condition under steady states given a set of parameters such as load demand and real power generation.

In a distribution system, there is typically one voltage specified bus, the substation bus, which is connected radially to the load buses. The solution to the power flow problem provides information on the voltage magnitudes and angles at each bus, the real and reactive power supplied or absorbed at the substation, the real and reactive power flows in each line section, and the system losses.

With the invention and wide spread use of digital computers in 1950s, many methods for solving the power flow problem have been developed such as indirect Gauss-seidal (buses admittance matrix), direct Gauss-seidal (bus impedance matrix), Newton-Raphson and its decoupled versions. However, these algorithms have been designed for transmission system, and therefore their application to the distribution systems usually does not provide good results and very often, the solution diverges. One of the reasons why these methods are unsuitable for distribution system is that they are mostly based on the general meshed topology of typical transmission systems whereas most distribution systems have a radial or tree structure. Another reason is due to the high R/X ratio of distribution systems. This is a factor causes the distributions to be ill-conditioned for conventional power flow methods [24].

The ladder network based load flow is used in this paper, which involves the equations of Kirchhoff's law. The forward sweep will determine a computed source voltage V_0 . For the first iteration of the load flow, it is assumed that all the end node voltages have a voltage of the reference node voltage (V_s) at the source node. The currents drawn by each of the loads are then calculated by:

$$I_i = \left(\frac{S_i}{V_i} \right)^* \quad 3-14$$

The currents flowing through each section of the feeder are calculated by summing the load currents downstream of the section. The node voltages can be then calculated by:

$$V_i = V_{i+1} + Z_{i+1} \cdot I_{i+1} \quad 3-15$$

The newly calculated voltages are used to recalculate the load currents using equation (3-14). The first iteration will produce a source node voltage that is not equal to the specified source voltage V_s . The backward sweep commences by using the specified source voltage and line currents from the forward sweep. Kirchhoff's voltage law also used in the backward sweep to compute the voltage at node $n+1$, which is given by equation 3-16.

$$V_{i+1} = V_i - Z_{i+1} \cdot I_{i+1} \quad 3-16$$

This procedure repeated for each line segment until a new voltage is determined at the last node. Using the voltage at the last node, a second forward sweep is started that will lead a new computed voltage at the source. The forward and backward sweep process is continued until the difference between the computed and the specified voltage at the source is within a given tolerance.

The real power losses of a line segment must be computed as the difference of the input power to a line segment minus the output power of the line segment.

The total loss in the feeder is obtained by:

$$S_{Loss} = \sum_{i=0}^{n-1} (v_i + v_j) \cdot I_{ij}^* \quad 3-17$$

Where

V_i and V_j are the line voltages of bus i and j respectively

j = the bus connected to bus i through branch i, j

I_{ij} = the line current flowing from bus j to bus i , n = the number of bus

The ladder iterative power flow solution methods are summarized in the flow chart in Figure 3-5

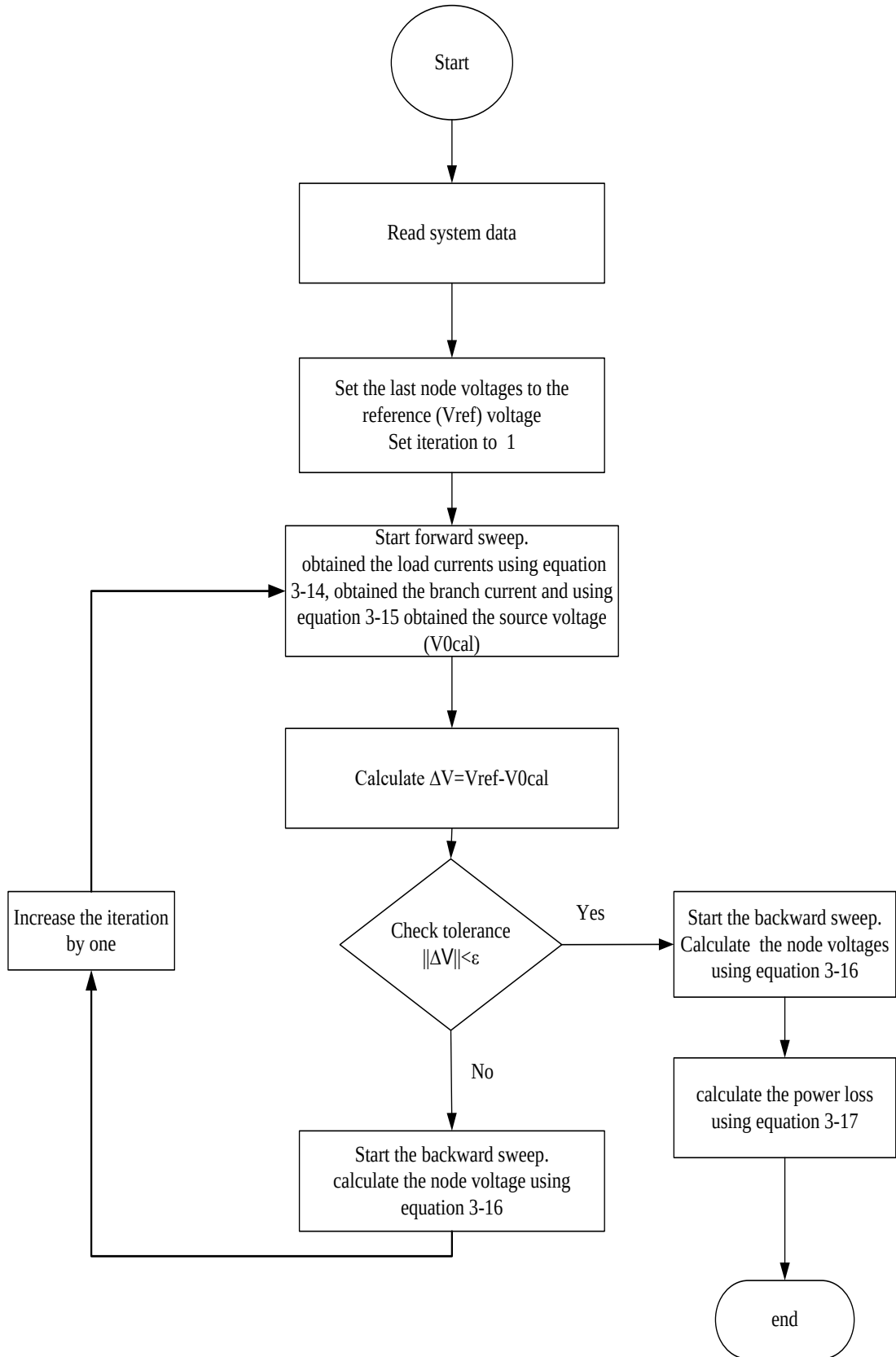


Figure 3-5 Flow chart for power flow solution using ladder iterative method

3.8. Distribution system loss reduction Technique

The methods for loss reduction are numerous. They include Demand Side Management programs, distribution transformer load management, reconfiguration, reconductoring, voltage up-rating, and FACTS device installation.

3.8.1. Demand Side Management

Some utilities have set up demand side management policies to recommend customers to defer the use of home appliances such as backing and cooking stoves, cloth washers and dryers to off-peak hours. The Ethiopian electric power corporation put a notice on electricity sale bill that there is high power demand between 9 to 11 A.M and 7 to 10 PM local time and recommends power demanding home electric appliances be used other than this time. To further increase the incentive of using electricity at off-peak times, some utilities have been established time-of-use rates with less expensive energy charges during off-peak hours. Time-of-use rates have been mandatory in California for all customers above 500 KW since 1978, as a state-wide policy response to the energy crises of 1973. These rates are mandatory in several U.S states but the size threshold varies by state. (J.Terry Cousins, Using time off use tariffs in industrial, commercial and residential applications effectively)

The effectiveness of a demand side management program depends on the participation of the customers. Using certain household appliances at off-peak times may not be convenient for some customers. In some instances, the encouragement of using electricity at non-peak times has even caused new peaks to occur. Furthermore, this form of power peak-shaving will have less effect in a deregulated environment like Ethiopia as the producers of electricity are likely to only have a Kwh rate and no KW rate for the demand. From an economic savings perspective, there is less motivation for the promotion of demand side management programs [4].

3.8.2. Distribution Transformer Load Management

Distribution transformer load management involves balancing the load between phases and resizing over and under-utilized transformers to reduce losses. Ideally, phase currents and voltages of all distribution transformers would need to be monitored in order to practice distribution transformer load management properly. However, for all Ethiopian utilities, such measurements are only available at the substation level.

To monitor every pole and pad mounted transformer downstream from the substation would prove to be costly. At the very least, distribution transformer load management can be practiced at the planning stages of a distribution system by sizing transformers for maximum efficiency.

3.8.3. Reconfiguration

Network reconfiguration refers to the closing and opening of switches in a power distribution system in order to alter the network topology, and thus the flow of power from the substation to the consumers. Many distribution systems have a radial structure and are equipped with sectionalizing switches for fault isolation or scheduled maintenance of a section. These switches can also be used to transfer loads between unevenly loaded feeders. During normal operating conditions, networks reconfigured for two purposes:

- i. To minimize the system real power losses in the network
- ii. To relieve the overload in the feeders. Loss reduction by reconfiguration is highly system dependent. Reconfiguration is less likely to be effective for systems with few automatic sectionalising switches which are the case of Ethiopian (particularly Woldia) power distribution systems.

3.8.4. Reconductoring

It is obvious that the use of feeder conductors with larger cross-sectional areas has associated lower losses. The more expensive larger sized cables and the installation costs are likely to forbid reconductoring as a feasible means for loss reduction. Moreover, feeder upgrades with heavier conductors can only be economical justified for older networks that are operating close to their design capacity.

3.8.5. Voltage Up-rating

By increasing the primary distribution systems voltage, the same amount of power can be delivered at lower currents, thus lowering losses. Voltage up-rating like reconductoring has required much capital expenditure (small benefit/cost ratio).

3.8.6. FACTS device

Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. Yet to achieve both operational reliability and financial profitability, it has become clear that more efficient utilization and control of the existing transmission system infrastructure are required. The challenge facing the power system engineer today is to use existing transmission facilities more effectively.

Certainly, great difficulty is encountered when seeking permission to construct new transmission lines. Equally certain, the loading required on the system is likely to increase as demand increases. Improved utilization of the existing power system is provided through the application of advanced control technologies. Power electronics based equipment, or FACTS, can provide technical solutions to address operating challenges being presented today.

A FACTS uses a power electronic-based device for the control of voltages and/or currents in a.c. transmission systems to enhance controllability and increase power transfer capability. It is an engineered system of advanced power semiconductor-based converters, information and control technologies (software), and interconnecting conventional equipment that builds intelligence into the grid by providing enhanced-power system performance, optimization, and control. Compared with the construction of new transmission lines, FACTS require minimal infrastructure investment, environmental impact, and implementation time.

shows the various types of traditional solutions, conventional FACTS solutions, and advanced FACTS solutions. Often, traditional system solutions can only partially reduce a transmission bottleneck; thus, other means are required. Many times, the advanced solution will allow the converter to respond to transient conditions and help improve the stability of the system in a way that a conventional FACTS converter cannot; the incremental cost for the additional flexibility and controllability may then be well justified [6].

3.8.6.1.1. Traditional FACTS Device

Traditional Solutions for Enhancing Power System Control including the following

- Series Capacitor
- Switched Shunt Capacitor and Reactor
- Transformer LTC
- Phase-Shifting Transformer
- Synchronous Condenser

3.8.6.1.2. Conventional FACTS Device

Conventional FACTS Solutions Line-commutated thyristor including the following

- Static Var Compensator (SVC)
- Thyristor-Controlled Series Compensator (TCSC)
- Thyristor-Controlled Phase-Shifting Transformer (TCPST)
- Inter-phase Power Flow Controller (IPFC)
- HVDC back to back as a power flow controller

3.8.6.1.3. Advanced FACTS Device

Advanced FACTS Solutions Self-commutated transistor including the following

- Static Synchronous Compensator (STATCOM)
- Unified Power Flow Controller (UPFC)
- Convertible Series Compensator (CSC)
- Static Synchronous Series Controller (SSSC)
- Voltage Source Converter (VSC)-based back-to-back dc link (BTB)
- Superconducting Magnetic Energy Storage (SMES)
- Battery Energy Storage System (BESS)

3.8.6.2.Comparison of Traditional Solutions and FACTS Solutions

Traditional solutions to upgrade the electrical transmission system infrastructure have been primarily in the form of new transmission lines, substations, and associated equipment.

However, as experiences have proved over the past decade or more, the process to permit, site, and construct new transmission lines has become extremely difficult, expensive, time-consuming, and controversial. FACTS technologies provide advanced solutions as alternatives to new transmission line construction.

The following is a brief summary of the advantages and disadvantages of the different device techniques used to control the voltage or power flow in a Transmission & Distribution system:

Traditional FACTS Device

- Slow-to-medium response speed (cycles to seconds)
- Limited switching cycles, stepped output
- Less expensive

Conventional FACTS Device

- Fast response speed (cycle)
- Unlimited switching, continuous smooth output
- More expensive

Advanced FACTS Device

- Ultrafast response speed (sub-cycle)
- Unlimited switching, continuous smooth output
- Even more expensive

Table 3-2 Steady state application of FACTS

Issue	Problem	Corrective action	Conventional solution	FACTS device
Voltage limits	Low voltage at heavy load	Supply reactive power	Shunt capacitor, Series capacitor,	SVC, TCSC, STATCOM
	High voltage at light load	Remove reactive power supply	Switch EHV line and/or shunt capacitor	SVC, TCSC, STATCOM
		Absorb reactive power	Switch shunt capacitor, shunt reactor	SVC, STATCO
	High voltage following outage	Absorb reactive power	Add shunt reactor	SVC, STATCO
		Protect equipment	Add arrestor	SVC
	Low voltage following outage	Supply reactive power	Switch shunt capacitor, shunt reactor, series capacitor	SVC, STATCO
		Prevent overload	Series reactor, PAR	TCPAR, TCSC
	Low voltage and overload	Supply reactive power and limit overload	Combination of two or more devices	TCSC, UPFC, STATCOM, SVC
Thermal limits	Line or transformer overload	Reduce overload	Add line or transformer	TCSC, UPFC, TCPAR
			Add series reactor	SVC, TCSC
	Tripping of parallel circuit (line)	Limit circuit (line) loading	Add series reactor, capacitor	UPFC, TCSC

4. DATA ANALYSIS

4.1. Methods and Materials

4.1.1. Data collection

Primary data are obtained through interview, direct observation and measurements. Secondary data are collected from literature (libraries and Internet) and data sheets of electric distribution substation.

4.1.2. Data analysis

Ladder iterative power flow algorithms are implemented in the radial distribution feeder before compensation using MATLAB computer programs to determine the total power losses, the voltage magnitude and angles at each bus and the currents flowing through each branch. To identify the nodes to be compensated repetitive applications of loss minimization technique is applied. Global size of capacitors for multiple nodes for capacitor placement is determined by optimizing the loss saving equations with respect to the capacitor currents. This technique is easy to apply and helps to identify the size of capacitors and locations for maximum loss reductions.

To determine the benefits obtained from the installation of capacitors in primary distribution networks, the power flow analysis programme run after the identified nodes compensated with the appropriate capacitor size selected. In conducting this research MATLAB software used. This thesis will not cover the practical implementation of the capacitors

To obtain the benefits from installation of shunt capacitors, it is necessary to select the appropriate place and size of capacitors for maximum benefits. For this work data are collected from EEU officials and EEP the substation data are taken from the feeder lines. From substation two feeders are considered for this work because this feeder incorporates all kind of loads such as industrial, commercial, and domestic and having long distance distribution networks. In addition, this feeder has a maximum demand at the substation. From these those feeders have high reactive power flow and their average power factors are recorded as 0.75, 0.73, and 0.78 for ‘Woldia-I’, ‘Woldia-II’ and ‘Mechary’ respectively at the substation. A random day daily power factors of three feeders are depicted in Figure 3-1 which is recorded at the substation.

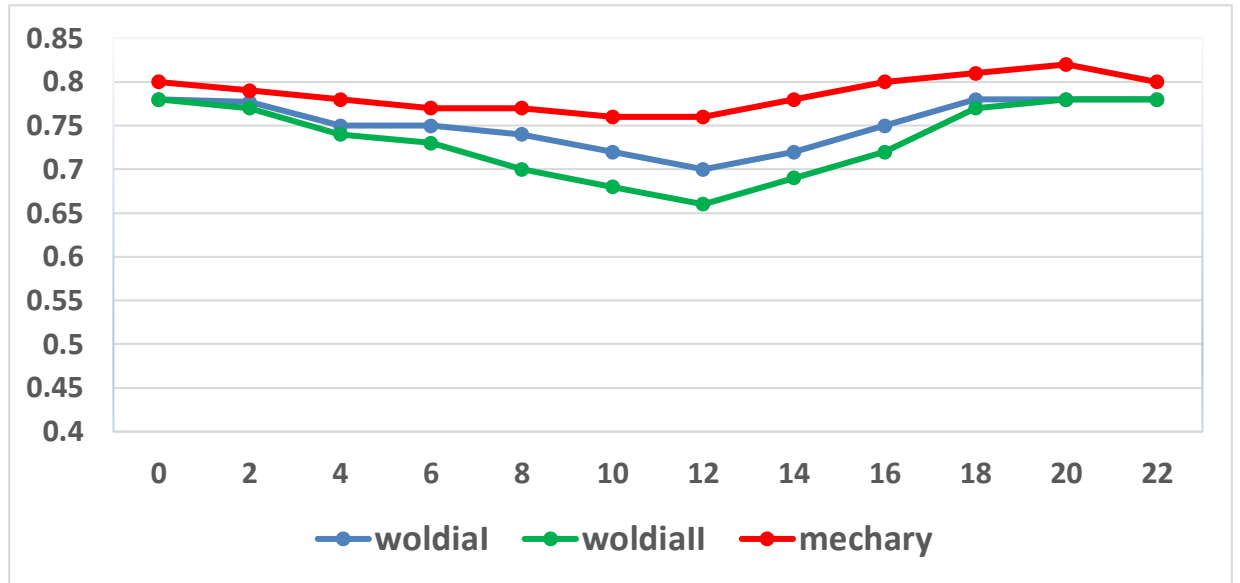


Figure 4-1 Power factors of Woldia-I, Woldia-II and Mechary feeders

4.2. Eighty-Two Bus Radial Distribution Feeder (Woldia-II)

In eighty-two bus feeder consists of a substation connected to node 0 which is taken as the reference node, 81 branches and 82 nodes of which 59 nodes are connected to loads through distribution transformers, the remaining 23 are common coupling nodes. A single line diagram of this feeder is shown in Figure 4-2, 73.673 km long all aluminium conductor (AAC-70 mm²) overhead lines are used to distribute medium voltage 15 KV power from substation to the distribution transformers. The conductors have the following arrangements as shown in Figure 4-3.

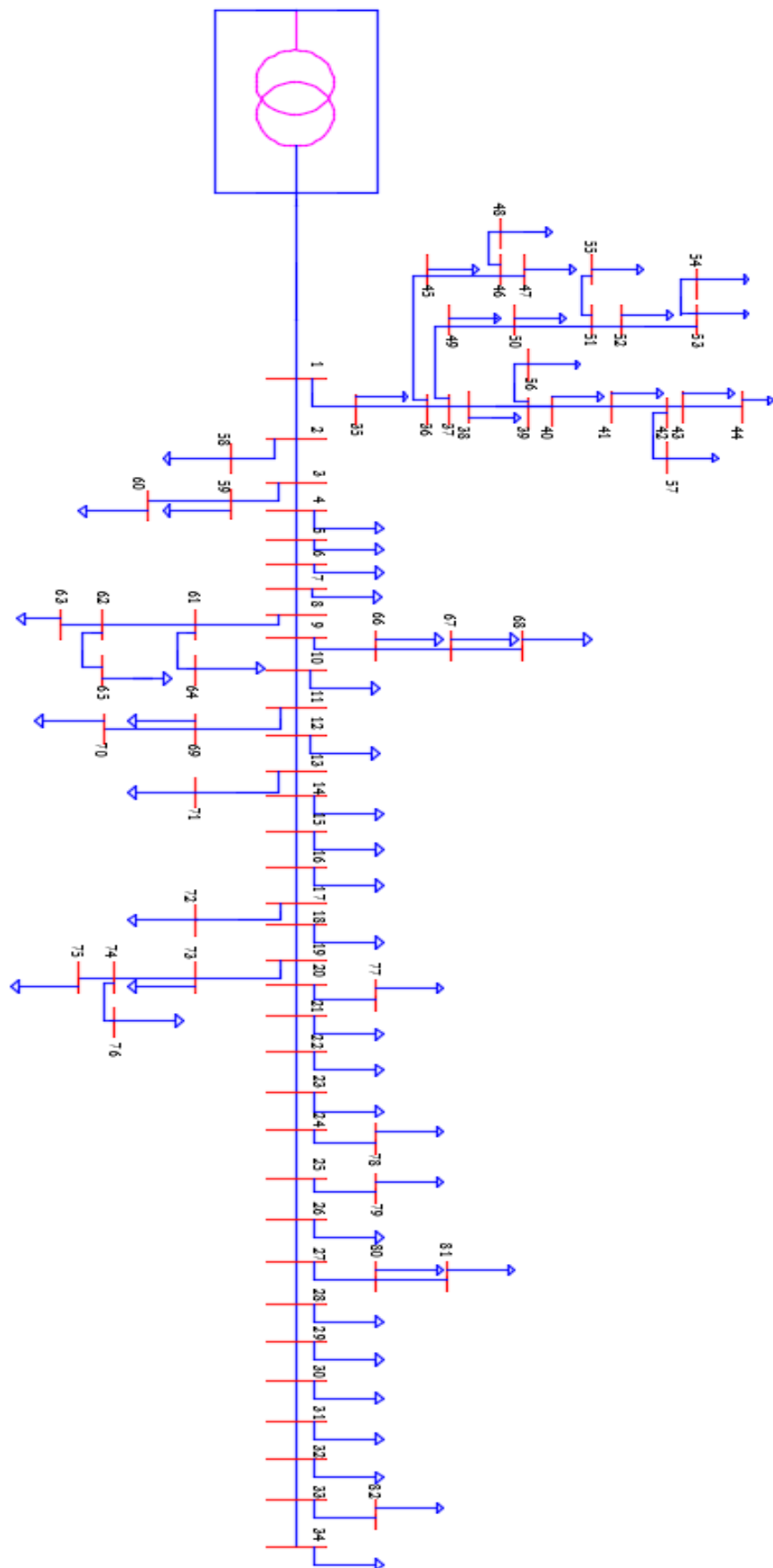


Figure 4-2 Single line diagram of eighty-two bus distribution system

The overhead conductors' parameters are given in Table 4-1 where the resistance of the conductors is obtained from the standard overhead conductor data sheet and the GMRs are calculated using equation 3-2 and Table 4-1.

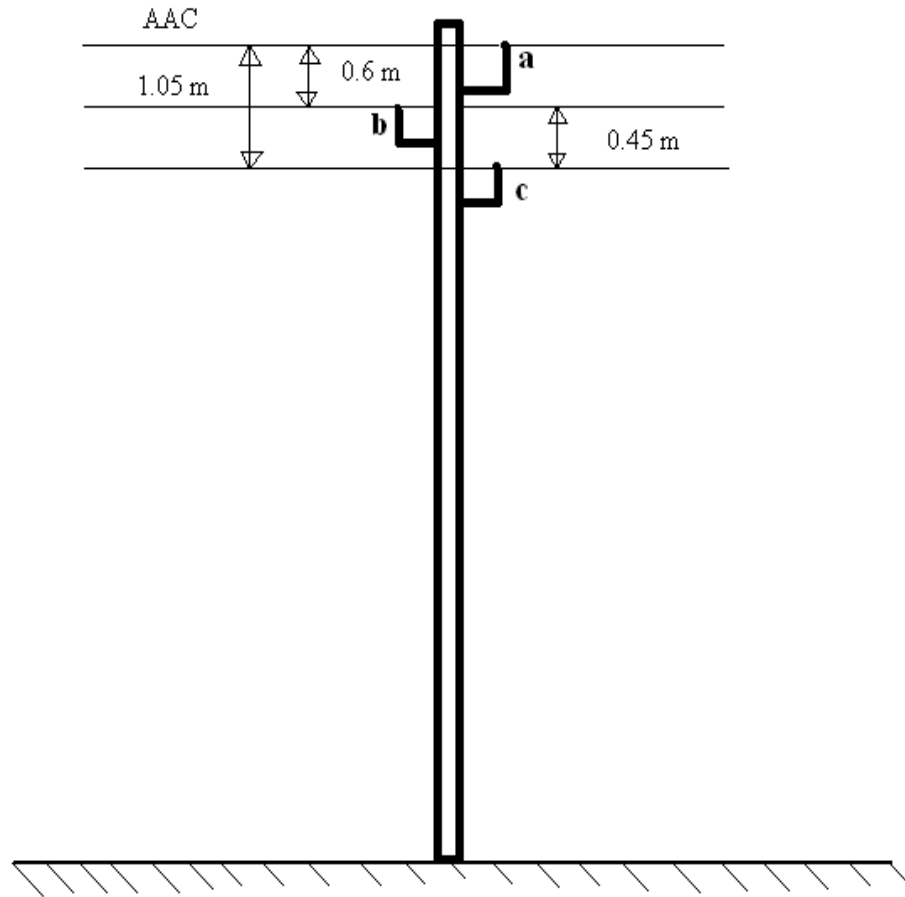


Figure 4-3 Overhead conductor arrangements

Conductor type	Nominal area (mm ²)	Actual area (mm ²)	Stranding and wire diameter	Overall diameter (mm)	Actual diameter (mm)	GMR (mm)	Resistance (Ω/km)
AAC	70	65.81	19/2.10	10.5	9.1538	3.468	0.4372
AAC	95	93.27	19/2.5	12.5	10.8975	4.129	0.3084

Table 4-1 Over head conductor data

Using equations 3-13, Figure 4-3 and Table 4-1 the branch positive sequence impedances are calculated detailed calculation is given in appendix B. By using Figure 4-2 the overhead conductor data and assuming that power factor of the distribution transformers is 80%, the maximum transformer loads demand (real and reactive demand) at the secondary of distribution transformers are tabulated in detailed is given in appendix B Table B-1.

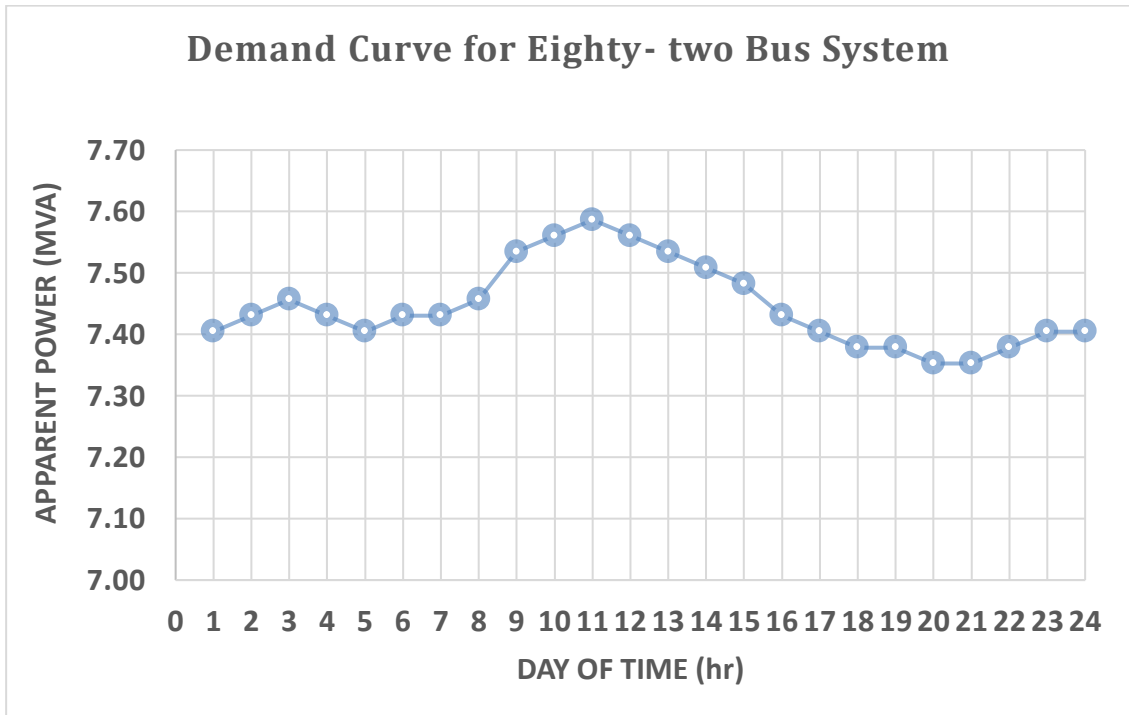


Figure 4-4 Demand curves of eighty-two bus system

4.3. Twenty-six-Bus Radial Distribution Feeder (Woldia-I)

Like eighty-two-bus feeder it has a radial configuration with twenty-six bus and 25 branches and 26 nodes of which 17 nodes are connected to loads through distribution transformers, the remaining 7 are common coupling nodes. The single line diagram at the substation of this feeder is shown in Figure 4-4. This feeder uses AAC-70 (total length of 15.07 km) conductor to distribute medium voltage 15 KV power to the distribution transformers.

Using equations 3-13, Figure 4-3 and Table 4-1 the branch positive sequence impedances are calculated detailed calculation is given in appendix B. By using Figure 4-4 the overhead conductor data and the maximum transformer loads demand (real and reactive demand) at the secondary of distribution transformers are tabulated in detailed is given in appendix Table B-2.

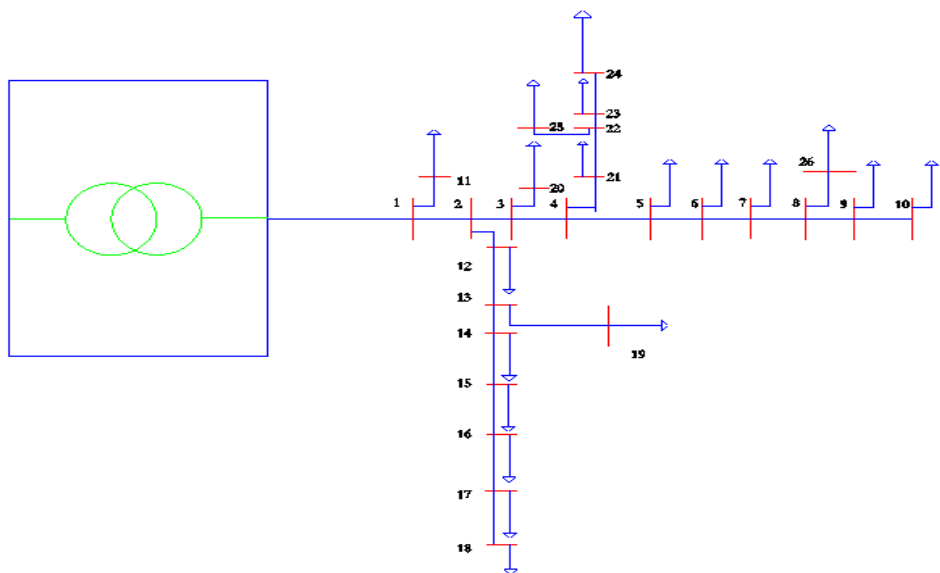


Figure 4-5 Single line diagram of twenty-six bus distribution system

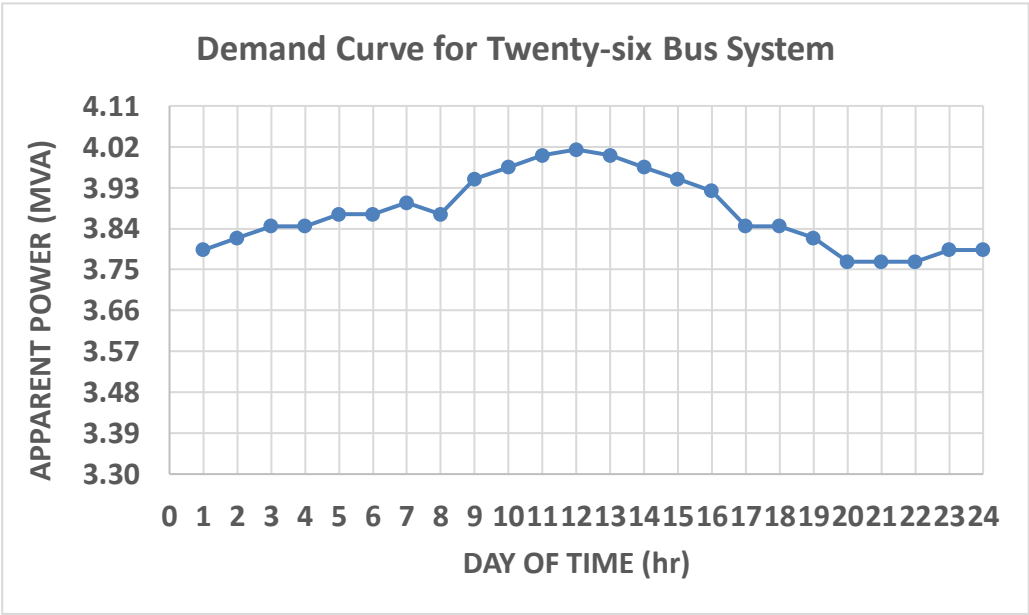


Figure 4-6 Demand curves of Twenty-six bus system

5. OPTIMAL LOCATION AND SIZE OF CAPACITORS ON A RADIAL DISTRIBUTION SYSTEM

5.1. Introduction

Electric power losses in distribution systems correspond to about 70% of total losses in electric power system. Portion of these losses are caused by the reactive current flowing in the network. These electric losses can be considerably reduced through the installation and control of reactive support equipment's, such as capacitor banks, reducing reactive currents in distribution feeders. The pressure of improving the performance of power delivery has forced the power utilities to reduce the loss, especially at the distribution level. Capacitors are widely installed in distribution systems for reactive power compensation to achieve power and energy loss reduction, power factor correction, system capacity release and to maintain a voltage profile within permissible limits.

Generally, distribution system is fed at only one point and the structure of the network is mainly radial. For such a system, all active power demands and losses must be supplied by the source at root bus. However, addition of shunt capacitors can generate the reactive power and therefore it is not necessary to supply all reactive power demands and losses by the source. Thus, there is a provision to minimize the loss associated with the reactive power flow through the branches.

The purpose of placing capacitors along distribution feeders is to lower the total power loss and bring the bus voltage within specified limits while minimizing the total power loss. The total I^2R power loss (P_{Tloss}) in a distribution system having n number of branches is given by [4]:

$$P_{Tloss} = \sum_{j=1}^n I_j^2 R_j \quad 5-1$$

Where R_j and I_j are the resistance and the line current magnitude respectively of the j^{th} branch, which is obtained from the load flow solution.

The branch currents have two components, namely,

- those due to the in-phase or active component of current and
- those due to the out-of-phase or reactive component of current.

$$I_j = I_{aj} + jI_{rj} \quad 5-2$$

The I^2R total loss is the summation of the losses associated with the active and reactive components of the branch currents. The I^2R loss associated with the active and reactive components of branch currents can be written as:

$$\begin{aligned} P_{TLoss} &= P_{La} + P_{Lr} \\ &= \sum_{j=1}^n (I_{aj}^2 R_j + I_{rj}^2 R_j) \end{aligned} \quad 5-3$$

$$P_{Lr} = \sum_{j=1}^n I_{rj}^2 R_j \quad \text{and} \quad P_{La} = \sum_{j=1}^n I_{aj}^2 R_j \quad 5-4$$

Shunt capacitors supply capacitive reactive power to the system at the point where they are connected, mainly to counteract the out-of-phase component of current required by an inductive load.

For a single source radial network, the active current component I_a depends only on the circuit load. The losses P_{La} due to the in-phase or active component of branch currents are not significantly affected by the application of shunt capacitors, they are not considered, because all active power must be supplied by the source at the root bus. However, the loss P_{Lr} associated with the reactive component of branch currents can be minimized by supplying part of the reactive power demand locally.

5.2. Optimal Locating of Capacitors

The method used here is first formulating the node-to-branch incidence matrix (G) of a given configuration. Using the node-to-branch incidence matrix, the sequence of node to be compensated is identified by repetitive applications of loss minimization technique. Once the sequence of nodes to be compensated is identified, the corresponding optimal size at the compensated nodes can be determined simultaneously by minimizing the loss saving equation with respect to the capacitor currents.

Node after branch determination: to determine the nodes after each branch of the feeder (G), first the branch-to-node incidence matrix IM is constructed. In IM the rows indicate the identification numbers of branch and the columns the identification numbers of nodes.

The generic elements IM (i ,j) are assumed to have the values significations of which are given below:

$$IM = (i, j) = \begin{cases} +1, & \text{if } j \text{ is the receiving end of branch } i \\ -1, & \text{if } j \text{ is the sending end of branch } i \\ 0, & \text{otherwise} \end{cases}$$

5-5

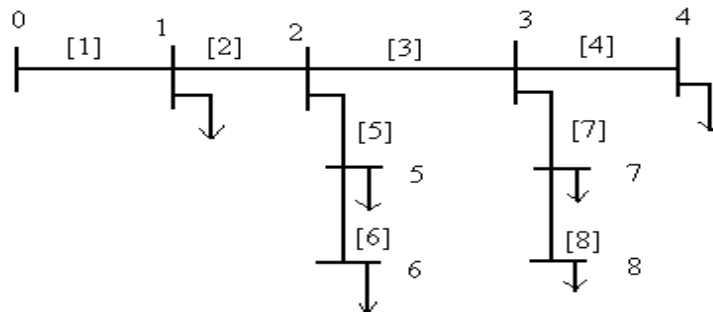


Figure 5-1 Nine node radial distribution feeder

For the feeder example of Figure 5-1, the branch-to-node incidence matrix is:

$$IM = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix}$$

From the branch-to-node incidence matrix, the node-to-branch incidence matrix G is deduced by simply inversion of IM. In the node-to-branch incidence matrix, the nodes identifiers are shown on rows and the column numbers identify the branches numbers.

For the feeder of Figure 5-1, the node-to-branch incidence matrix G is:

$$G = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Considering single source radial distribution system with n branches, let a capacitor C be placed at bus i. The capacitor draws a reactive current i_c and for radial network it changes only the reactive component of the current of branches between the source and the capacitor unit buses. The current of other branches is unaffected by the capacitors. Thus, the new reactive branch current I_r^* due the addition of capacitor at node i is given by:

$$I_{rj}' = I_{rj} + G_{ij} I_{ci} \quad 5-6$$

Where i_{rj} = the reactive current of the jth branch in the original system obtained from the load flow solutions

G_{ij} = the ith row and jth column elements of matrix G

The loss P_{Lr} associated with the reactive component of branch currents when the capacitor is connected in the compensated system can be written as:

$$P_{Lr}' = \sum_{j=1}^n (I_{rj} + G_{ij} I_{ci})^2 R_j \quad 5-7$$

The loss saving ΔP_{LSi} which is obtained due to the capacitor current I_{ci} at bus i is:

$$\begin{aligned} \Delta P_{LSi} &= P_{Lr} - P_{Lr}' = \sum_{j=1}^n I_{rj}^2 R_j - \sum_{j=1}^n (I_{rj} + G_{ij} I_{ci})^2 R_j \\ \Delta P_{LSi} &= - \sum_{j=1}^n (2 I_{rj} G_{ij} I_{ci} + G_{ij}^2 I_{ci}^2) R_j \end{aligned} \quad 5-8$$

The capacitor current that provides the maximum loss saving can be obtained from differentiating the loss saving of equation 5-8 with respect to the capacitor currents and equating to zero:

$$\frac{\partial \Delta P_{LSi}}{\partial I_{ci}} = -2 \sum_{j=1}^n (G_{ij} I_{rj} + G_{ij} I_{ci}) R_j = 0$$

$$I_{ci} = - \frac{\sum_{j=1}^n G_{ij} A_j}{\sum_{j=1}^n G_{ij} R_j} \quad 5-9$$

Where

$$A_j = I_{rj} \cdot R_j, j = 1, 2, \dots, n$$

The corresponding capacitor size is given by:

$$Q_{ci} = V_i \cdot I_{ci} \quad 5-10$$

Where V_i is the voltage magnitude of capacitor bus i .

The above process helps to identify the capacitor bus that resulted highest loss savings. When the candidate bus is identified and compensated, the above technique also be used to identify the next and subsequent nodes.

5.3. Optimal Sizing of Capacitors

Once a suitable sequence of capacitor location is found using singly located capacitors at each bus, the next step is to find the global optimal size of capacitors of the system. The capacitors obtained in equation 5-10 is a local optimum values, but not a global optimum. From the node-to-branch incidence matrix, identify and select the whole row of the compensated buses identifiers (i), and take the transposed (G^c).

$$G^c = [G(i,:)]^T \quad 5-11$$

Where $i = 1, 2, 3, \dots, k$, k - the number of capacitor buses

The new reactive component of branch currents after the buses are compensated by the capacitors is given by

$$[I_{rj}'] = [I_r] + [G_{ji}^c] I_{ci} \quad 5-12$$

The loss P_{Lr}'' associated with the new reactive current is

$$P_{Lr}'' = -\sum_{j=1}^n (I_{rj} + [G_{ji}^c] I_{ci})^2 R_j \quad 5-13$$

The loss saving due to the capacitor placement is the difference between equation 5-4 and 5-13

$$\begin{aligned} \Delta P_{LSi} &= P_{Lr} - P_{Lr}'' \\ \Delta P_{LS}' &= -\sum_{j=1}^n (2I_{rj} [G_{ji}^c] I_{ci} + ([G_{ji}^c] I_{ci})^2) R_j \end{aligned} \quad 5-14$$

Maximizing the loss saving of equation 5-14 is given by

$$\frac{\partial \Delta P_{LSi}}{\partial I_{ci}} = 0 \quad 5-15$$

Solving I_c from equation 5-15 is given by a set of linear algebraic equations as

$$[C][I_c] = [D] \quad 5-16$$

The capacitor currents for the maximum loss saving can be obtained

$$[I_c] = [C]^{-1} [D] \quad 5-17$$

Where C is a KxK square matrix and D is a K-dimensional vector. The elements of C and D are given by

$$C_{mk} = \sum_{j=1}^n (G_{jm}^c \cdot G_{jk}^c) R_j \quad 5-18$$

$$D_k = -\sum_{j=1}^n G_{jk}^c I_{rj} R_j \quad 5-19$$

Where k - the number of capacitor buses

I_c - k dimensional vector of capacitor currents

The global optimum capacitor size can be written as

$$[Q_{copt}] = [V_c][I_c] \quad 5-20$$

Where V_c - the voltage magnitude of capacitor buses

5.4. Switched Capacitors

Fixed capacitors are suitable for steady loads which do not have a large variance. For loads that swing widely and have a shorter lasting peak, switched capacitors are more appropriate.

One way of determining whether a load is considered as a steady or has a short-lasting peak is by examining its load and loss factor. Average Power Loss Peak Power Loss

By definition, load factor is

$$F_{LD} = \frac{\text{Average Load}}{\text{Peak Load}} \quad 5-21$$

Thus, a load factor approaching the value 1 indicates that the average load is very close to the peak and the load is steady. However, a low load factor indicates the opposite, of a load that has more variation with time. Similarly, the loss factor is defined as

$$F_{LS} = \frac{\text{Average Power Loss}}{\text{Peak Power Loss}} \quad 5-22$$

The loss factor only applies to the I^2R loss of the system. Therefore, a loss factor approaching to the value 1 indicates that the load currents are quit steady; whereas smaller loss factor indicates more varying load currents and:

If the load is steady, the value of the loss factor approaching the value of the load factor, $F_{LS} \rightarrow F_{LD}$

If the load has a very short-lasting peak, the value of the loss factor approaches to the square of the load factor, $F_{LS} \rightarrow F_{LD}^2$

Therefore, in general the value of the loss factor is

$$F_{LD}^2 < F_{LS} < F_{LD} \quad 5-23$$

Using above relationship, the approximate formula for loss factor is given by

$$F_{LS} = 0.3F_{LD} + 0.7F_{LD}^2 \quad 5-24$$

Using equation 5-24, several rules can be established to determine where a suitable capacitor location requires a fixed or switched capacitor.

The rules are:

- If the load factor is approaching a value of 1 or is considered high, the loss factor is also high indicating that the load is steady, and then only a fixed capacitor is required.
- If the load factor is low, the loss factor is even lower indicating that the load varies widely with a shorter peak, and a much higher loss occur during the peak, then a switched capacitor is desired

Further investigating of the load factor also aid in determining the sizes of the switched capacitor required for the nodes suited for switched capacitors. The optimum level of reactive compensation is best when the value of the per-unit total reactive compensation is close to the loss factor.

Thus, using this correlation, and given the above equation, the following rules can be established to determine if the node is suitable for switched capacitor and also the amount of compensation level that should be switched on during peak period.

- If load factor, is high, then use only a fixed capacitor of the size, 100% of the compensation level found
- If load factor, is medium, then use a fixed capacitor of the size, $(0.3F_{LD} + 0.7F_{LD}^2)$ x100% of the compensation level found and a switched capacitor for the remainder of the compensation level.
- If load factor, is low, then use a fixed capacitor of the size F_{LD}^2 x100% of the compensation level found and a switched capacitor for the remainder of the compensation level. The decision values for low, medium and high is given in as less than 0.35, between 0.35 and 0.65 and greater than 0.65 respectively.

5.5. Algorithm

The load flow program calculates the branch currents, the node voltage magnitude and phase angle, and the real and reactive power loss before compensation. The reactive currents and the node voltages are used to obtain the maximum loss savings and the corresponding capacitor sizes. These maximum losses saving determine the node most suited for capacitor installation. By compensating the selected bus with the corresponding capacitors, the process repeats until a significant loss saving is achieved. Once the nodes are identified, the optimal size of capacitors to be placed at the chosen nodes is determined using the loss minimization techniques for multiple capacitor locations. Using the Load factors of the compensated node the need and size of the switched capacitors are determined. Finally, the load flow program runs to calculate the power loss reduction, the node voltage and branch currents after compensation

Figure 5-2 illustrates the flow of data through the individual components for the study of capacitor placement.

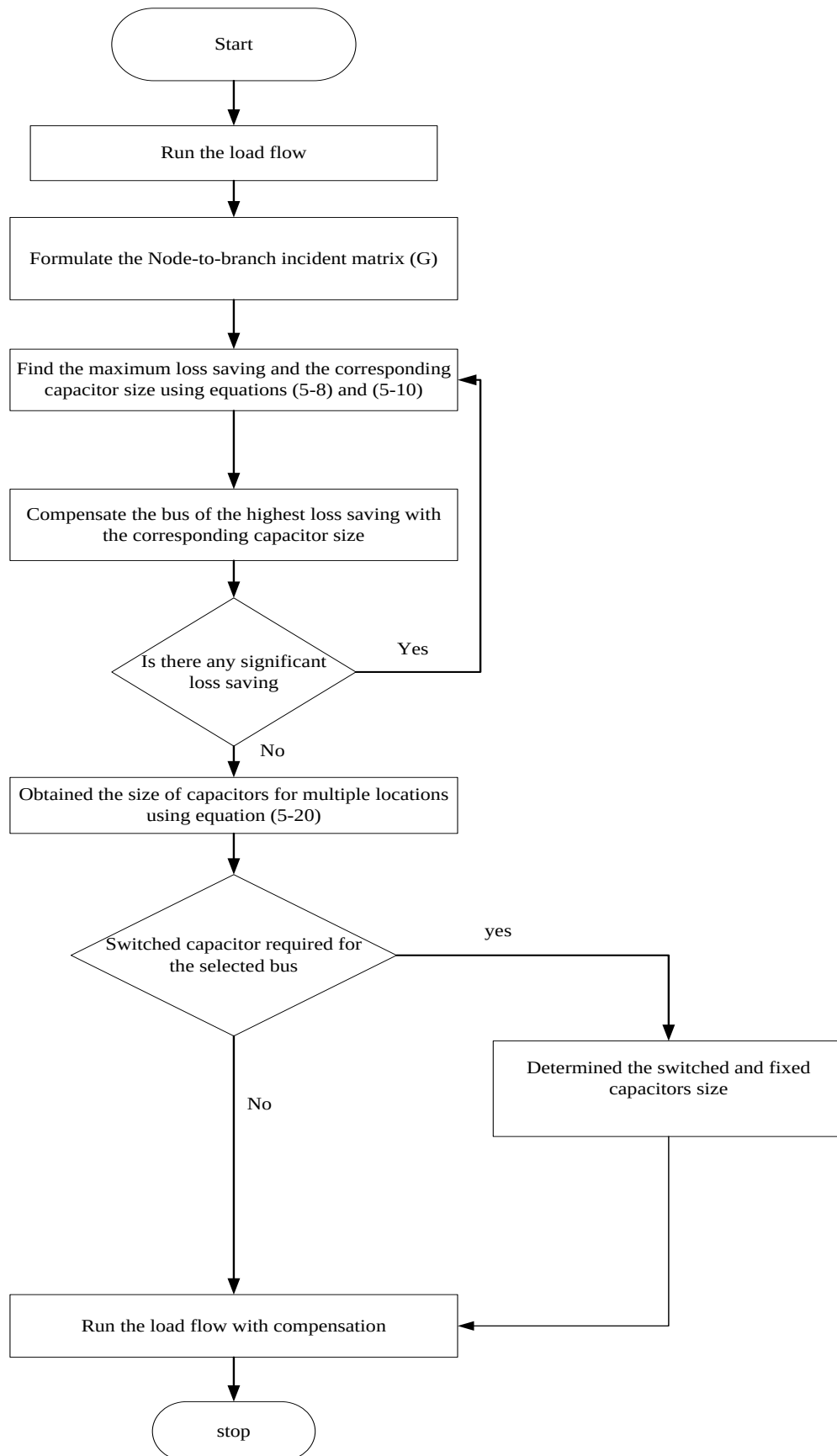


Figure 5-2 Flow chart

6. RESULTS AND DISCUSSIONS

Before solving the capacitor placement, it is important to find the node voltages and branch currents at each node of the distribution system. The branch currents are used to calculate the real and reactive power loss at each branch and the node voltages are used to find the size of capacitors needed to be installed. The algorithm given in section 5.5 is used on eighty-two and twenty-six bus radial feeders of Figure 4-2 and 4-4 respectively. The power flow method given in chapter three is implemented on these feeders using MATLAB R2010a software used to analyse complex analysis.

6.1. Analysis on Feeder Models

6.1.1. Eighty-two Bus Radial Distribution Feeder

The single line diagram, the line and load data of 15 KV, eighty-two bus system which are given in Figure 4-2 and appendix B Table B-1 respectively are consider.

The power flow analysis given in chapter three is used to find the node voltages and the total real and reactive power losses before compensation and the results are given in Table 6-1.

Table 6-1 Power flow solution of eighty-two bus system before compensation

Bus No	Voltage magnitude (KV)	Angle (degrees)	Bus No	Voltage magnitude (KV)	Angle (degrees)
1	14.889647	-0.064405	42	14.636471	-0.215400
2	14.794599	-0.120735	43	14.626125	-0.221679
3	14.691060	-0.182944	44	14.619658	-0.225608
4	14.590617	-0.244155	45	14.777735	-0.130510
5	14.494205	-0.303678	46	14.774654	-0.132343
6	14.408356	-0.357352	47	14.772601	-0.133565
7	14.346071	-0.396685	48	14.773628	-0.132954
8	14.271781	-0.444047	49	14.713418	-0.168967
9	14.215847	-0.480063	50	14.707261	-0.172665
10	14.171577	-0.508787	51	14.690837	-0.182541
11	14.124257	-0.539695	52	14.672874	-0.193367
12	14.070239	-0.575253	53	14.668101	-0.196249
13	14.018271	-0.609727	54	14.666715	-0.197086

14	13.863935	-0.713659	55	14.690323	-0.182849
15	13.715503	-0.815698	56	14.692244	-0.181694
16	13.521604	-0.952330	57	14.634336	-0.216695
17	13.142026	-1.231532	58	14.792257	-0.122125
18	12.960545	-1.370908	59	14.687980	-0.184798
19	12.795233	-1.501219	60	14.686131	-0.185911
20	12.662697	-1.608240	61	14.259161	-0.452109
21	12.600535	-1.659232	62	14.253005	-0.456047
22	12.542414	-1.707344	63	14.250954	-0.457361
23	12.488347	-1.752485	64	14.252698	-0.456244
24	12.396475	-1.830055	65	14.248902	-0.458674
25	12.378901	-1.845027	66	14.209180	-0.484355
26	12.369867	-1.852743	67	14.206616	-0.486007
27	12.363950	-1.857803	68	14.206103	-0.486338
28	12.359259	-1.861819	69	14.119128	-0.543040
29	12.354413	-1.865969	70	14.115026	-0.545717
30	12.349208	-1.870430	71	14.016733	-0.610745
31	12.345381	-1.873712	72	13.136908	-1.235396
32	12.318837	-1.896525	73	12.729798	-1.553651
33	12.308622	-1.905326	74	12.717527	-1.563542
34	12.304536	-1.908851	75	12.713437	-1.566844
35	14.837633	-0.095009	76	12.701166	-1.576761
36	14.784921	-0.126238	77	12.660571	-1.609972
37	14.744191	-0.150525	78	12.391080	-1.834642
38	14.716769	-0.166953	79	12.372771	-1.850255
39	14.692758	-0.181385	80	12.360456	-1.860789
40	14.669261	-0.195554	81	12.359026	-1.862012
41	14.649958	-0.207227	82	12.306579	-1.907088
<i>Total power loss</i>					
<i>Active power loss=402.4570 KW</i>					
<i>Reactive power loss=408.9708 Kvar</i>					

6.1.1.1. Results due to Capacitor Placement

The eighty-two buses radial distribution feeder has a total load of (6,124+j4,593) KVA and the total losses associated with the active and reactive power are 402.4570 KW and 408.9708 Kvar respectively.

The approximate loss saving due to the supply of reactive component of current using shunt capacitor at each node and the respective capacitor size is obtained by using equations 5-8 up to 5-10. The results are as given in Table 6-2

Table 6-2 Loss saving due to capacitor placement at each node

Bus No	Loss savings (KW)	Capacitor size (Kvar)	Bus No	Loss savings (KW)	Capacitor size (Kvar)
1	0.066642	106.95	42	1.288355	1218.76
2	2.182320	3695.54	43	1.245545	1144.83
3	1.869743	3396.71	44	1.163888	1051.11
4	3.853522	3228.69	45	1.076806	1682.52
5	4.604320	3101.51	46	0.876279	1350.18
6	5.269866	3016.53	47	0.738483	1127.43
7	5.711697	2945.06	48	0.731825	1122.41
8	6.186248	2849.30	49	1.000600	1207.16
9	6.447262	2746.77	50	0.910223	1074.57
10	6.610508	2657.43	51	0.671119	749.34
11	6.499117	2059.31	52	0.527779	556.24
12	6.886494	2448.83	53	0.458669	476.29
13	7.004824	2350.26	54	0.407254	421.10
14	7.427747	2129.65	55	0.620745	691.92
15	7.860635	1971.70	56	1.171224	1313.85
16	8.470111	1819.45	57	1.161438	1092.12
17	9.745872	1618.36	58	1.303593	2158.96
18	10.340582	1542.40	59	2.238371	2477.15
19	10.796717	1470.39	60	1.811995	1993.22
20	10.964872	1393.81	61	5.612359	2538.63
21	11.024945	1358.34	62	5.079103	2277.48
22	11.057614	1323.91	63	4.601433	2057.33
23	11.063708	1290.45	64	5.083295	2278.37
24	10.965457	1224.63	65	4.626714	2062.68
25	10.935793	1211.38	66	5.820728	2457.75
26	10.740529	1203.03	67	5.266822	2216.27
27	10.872781	1196.10	68	4.789824	2014.17
28	10.830133	1188.83	69	6.181003	2328.07
29	10.769493	1179.54	70	5.691545	2133.14
30	10.693340	1168.40	71	5.562908	1863.34
31	10.627118	1159.12	72	9.031777	1495.06

32	10.108291	1089.23	73	9.431696	1240.98
33	9.540534	1023.29	74	9.131973	1193.91
34	8.214792	993.05	75	8.793792	1147.26
35	1.284065	2758.09	76	8.542869	1107.49
36	1.368354	2210.62	77	10.715713	1360.66
37	1.426512	1932.15	78	10.473191	1166.72
38	1.414011	1726.49	79	10.582061	1168.87
39	1.372111	1541.83	80	10.748973	1181.18
40	1.352784	1409.81	81	10.487986	1151.74
41	1.335930	1313.70	82	8.985867	962.90
<i>The maximum loss saving is obtained at node 23</i>					

From the appendix C Table C-1 and C-2 the next bus to be compensated is bus 8 and 41 which has the maximum loss savings of 13.9664 KW using 1,369.62 Kvar capacitors and 6.6837 KW using 877.95 Kvar capacitors are respectively. Therefore the optimum location and sequence of nodes to be compensated for the maximum loss savings are 8, 23, and 41 respectively.

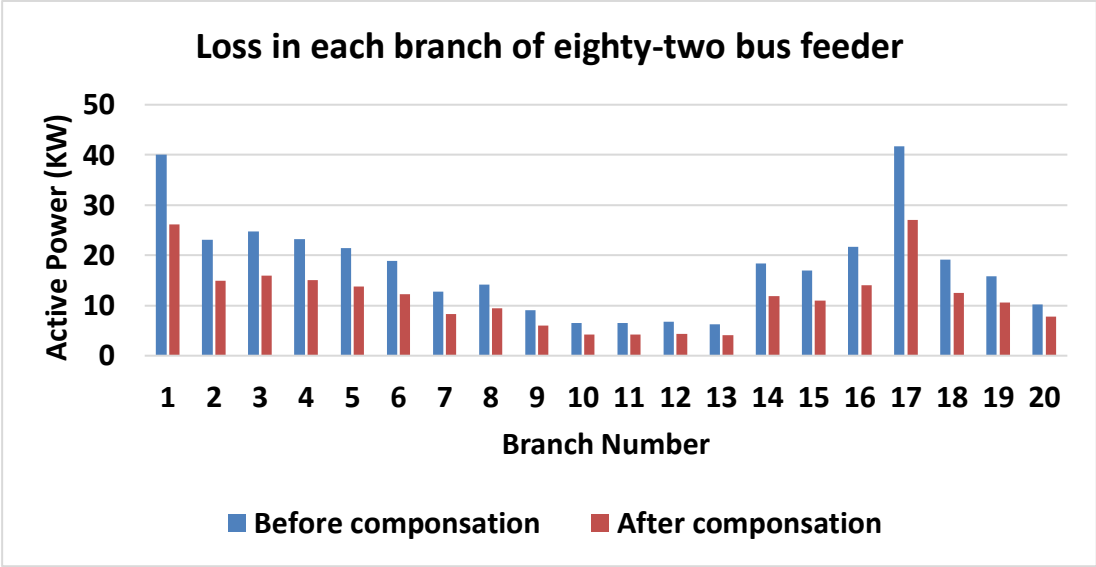
The capacitor obtained using equation 5-10 that required compensating the nodes are local maximum values. Therefore, it is necessary to find the global maximum values. Using equations 5-11 up to 5-20 the global optimum capacitor sizes are obtained as 1,428.41 Kvar, 266.80 Kvar and 988.07 Kvar for buses 8, 23 and 41 respectively. When the capacitor sizes are rounded to the nearby standard sizes, it becomes 1,500 Kvar, 300 Kvar and 1,000 Kvar for nodes 8, 23 and 41 respectively. The respective capacitor currents are 199.6455 A, 103.3323 A and 89.6726 A. Load flow is run after the identified buses are compensated with the selected capacitor sizes and the results are tabulated in Table 6-3

Table 6-3 Load flow solutions for eighty-two bus feeders after compensation

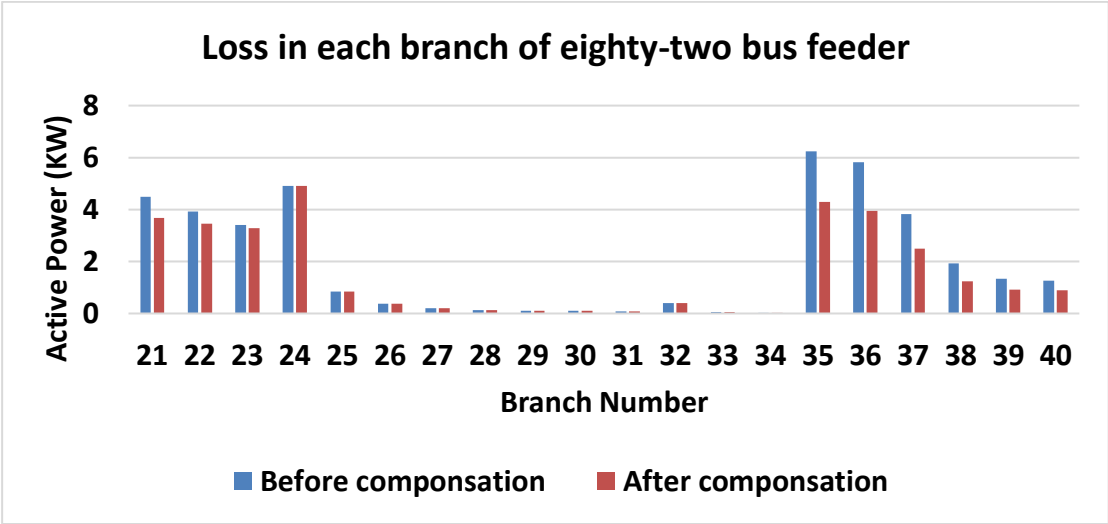
Bus No	Voltage magnitude (KV)	Angle (degrees)	Bus No	Voltage magnitude (KV)	Angle (degrees)
1	14.930256	-0.425758	42	14.775297	-0.746970
2	14.874899	-0.656639	43	14.764966	-0.751092
3	14.815672	-0.887376	44	14.758508	-0.397401
4	14.759762	-1.116956	45	14.848135	-0.399280
5	14.708129	-1.324300	46	14.845056	-0.400533
6	14.662774	-1.483226	47	14.843004	-0.399907

7	14.632111	-1.684348	48	14.844030	-0.490136
8	14.598625	-1.793518	49	14.798059	-0.493946
9	14.561687	-1.886107	50	14.791907	-0.504122
10	14.534056	-1.989926	51	14.775498	-0.515279
11	14.505784	-2.116450	52	14.757552	-0.518247
12	14.475614	-2.241939	53	14.752782	-0.519110
13	14.447552	-2.620133	54	14.751397	-0.504441
14	14.365310	-2.997076	55	14.774985	-0.604334
15	14.289614	-3.502071	56	14.803921	-0.741740
16	14.193620	-4.524505	57	14.773165	-0.741740
17	14.012962	-5.037531	58	14.872560	-0.427188
18	13.932416	-5.539317	59	14.812597	-0.658576
19	13.868916	-6.010907	60	14.810751	-0.659738
20	13.838648	-6.243059	61	14.586052	-1.693301
21	13.827884	-6.470994	62	14.579919	-1.697674
22	13.821319	-6.694556	63	14.577875	-1.699132
23	13.818948	-6.797372	64	14.579612	-1.697893
24	13.728875	-6.817197	65	14.575830	-1.700591
25	13.711647	-6.827410	66	14.555045	-1.798308
26	13.702791	-6.834106	67	14.552491	-1.800152
27	13.696991	-6.839421	68	14.551980	-1.800521
28	13.692393	-6.844913	69	14.500678	-1.993695
29	13.687643	-6.850814	70	14.496594	-1.996711
30	13.682542	-6.855157	71	14.446021	-2.243101
31	13.678790	-6.885337	72	14.007903	-4.529326
32	13.652773	-6.896978	73	13.804468	-5.606674
33	13.642761	-6.901640	74	13.792383	-5.619375
34	13.638757	-0.302656	75	13.788354	-5.623614
35	14.892410	-0.393019	76	13.776270	-5.636344
36	14.855316	-0.471133	77	13.836557	-6.013162
37	14.828806	-0.535935	78	13.723586	-6.803448
38	14.814193	-0.604013	79	13.705638	-6.824120
39	14.804434	-0.671856	80	13.693566	-6.838060
40	14.795208	-0.731807	81	13.692164	-6.839679
41	14.788765	-0.740382	82	13.640759	-6.899309
<i>Total power loss</i>					
<i>Active power loss= 158.437311 KW</i>					
<i>Reactive power loss= 170.425441 Kvar</i>					

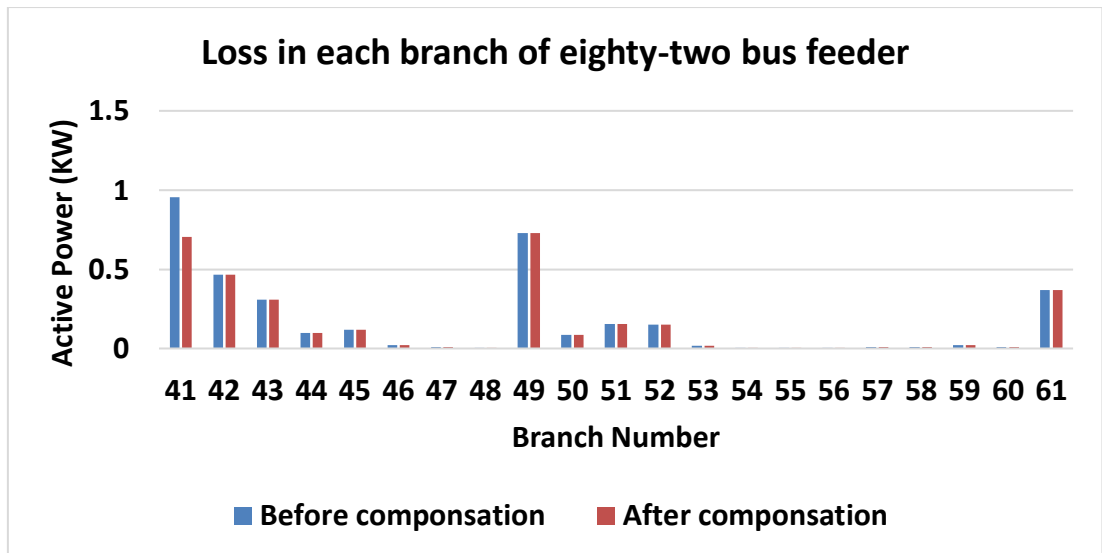
From Table 6-3 the total active power loss after compensation is found to be 158.4373 KW and before compensation was 402.4570 KW. Therefore, the loss saving is obtained as 244.0197 KW with the total capacitor size of 2,800 Kvar. The losses in each branch is reduced after loss optimization, it is clearly shown in Figure 6-1



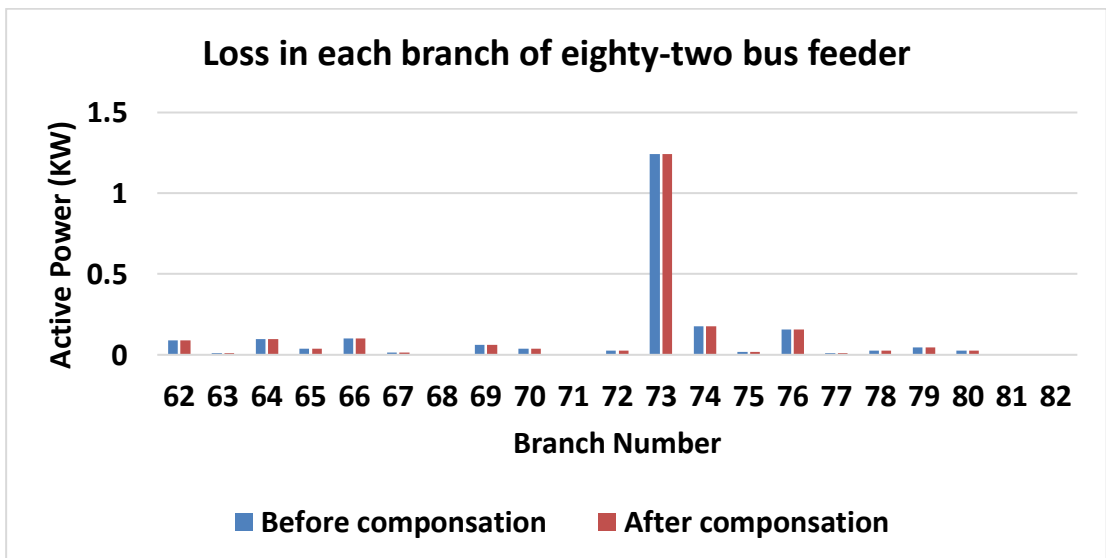
A



B



C



D

Figure 6-1 Loss of each branch reduced

From Table 7-3, it is observed that the voltage profile is improved after the selected node is compensated. The minimum node voltage which was 0.8203029 Pu before compensation becomes 0.9092505 Pu after compensation.

6.1.2. Twenty-Six Bus Radial Distribution Feeder

In this section, the single line diagram which is given in Figure 4-4 and its data and Appendix B Table B-2 are considered. Like eighty-two buses feeder rated substation voltage of 15 KV are used. The load flow results of twenty-six bus feeder before compensation is obtained as in Table 6-4.

Table 6-4 Power flow solution of a twenty-six bus system

Bus No	Voltage magnitude (KV)	Angle (degrees)	Bus No	Voltage magnitude (KV)	Angle (degrees)
0	15.000000	0.000000	14	14.589006	-0.242981
1	14.916343	-0.048359	15	14.565509	-0.257307
2	14.668519	-0.194886	16	14.548054	-0.267990
3	14.559569	-0.260900	17	14.533829	-0.276724
4	14.411517	-0.352199	18	14.527621	-0.280544
5	14.372762	-0.376385	19	14.614090	-0.227750
6	14.340457	-0.396689	20	14.555709	-0.263266
7	14.317191	-0.411391	21	14.398761	-0.360183
8	14.301678	-0.421232	22	14.393630	-0.363400
9	14.290044	-0.428626	23	14.390860	-0.365137
10	14.284227	-0.432330	24	14.389834	-0.365781
11	14.915316	-0.048958	25	14.391783	-0.364558
12	14.643219	-0.210127	26	14.295214	-0.425341
13	14.614552	-0.227469			
Total power loss					
Active power loss= 110.507528 KW					
Reactive power loss= 112.296075 Kvar					

6.1.2.1. Results Due to Capacitor Placement

This twenty-six bus radial distribution feeder has a total load of (3,260+j2,445) KVA. The total losses associated with the active and reactive power in the distribution line are 110.5075 KW and 112.2961 Kvar respectively.

The approximate loss saving due to the supply of reactive component of current using shunt capacitor at each node and the respective capacitor size is obtained by using equations 5-8 up to 5-10. The results are as given in Table 6-5.

Table 6-5 Approximate loss savings and capacitor sizes of twenty-six bus system

Bus No	Loss savings (KW)	Capacitor size (Kvar)	Bus No	Loss savings (KW)	Capacitor size (Kvar)
1	0.541815	116.18	14	9.451717	1669.40
2	22.806225	2368.96	15	9.405894	1541.76
3	26.845807	2082.98	16	9.232656	1439.80
4	32.175055	1849.16	17	8.703879	1320.45
5	32.878141	1767.97	18	8.017613	1220.31
6	33.030530	1685.34	19	5.924868	1929.35
7	32.711241	1609.55	20	23.618068	1816.15
8	32.048964	1540.26	21	29.905153	1680.76
9	26.564312	1460.65	22	27.662448	1541.01
10	29.473638	1380.27	23	25.811581	1431.09
11	2.975680	1230.51	24	23.897171	1322.63
12	10.147278	2077.90	25	25.733382	1429.01
13	9.568068	1829.74	26	30.251661	1439.90
<i>The maximum loss saving is obtained at node 6</i>					

From Table 6-5 the maximum loss savings is 33.0305Kw which is obtained by compensating node 6 with 1,685.34 Kvar capacitors. Therefore, the first candidate bus to be compensated is bus 6. The same process and equations 5-6 up to 5-10 are used to find the next bus to be compensated after compensated bus 6 and the results are depicted in appendix C Table C-3.

From these the next bus to be compensated is bus 17 which has the maximum loss savings of 3.298153 KW using 641.68 Kvar capacitors. The same equations and process are used to get the next bus to be compensated until insertion of capacitors has no such a significant loss savings. Therefore the optimum location and sequence of nodes to be compensated for the maximum loss savings are 6, and 17 respectively.

The capacitor obtained using equation 5-10 that required compensating the nodes are local maximum values. Therefore, it is necessary to find the global maximum values. Using equations 5-11 up to 5-20 the global optimum capacitor sizes are obtained as 1,678.38 Kvar and 822.26 Kvar for buses 6 and 17 respectively. When the capacitor sizes are rounded to the nearby standard sizes, it becomes 1,750 Kvar and 850 Kvar for nodes 6 and 17 respectively.

The respective capacitor currents are 137.7800A and 48.2980 A. Load flow is run after the identified buses are compensated with the selected capacitor sizes and the results are tabulated in Table 6-6.

Table 6-6 Power flow solution of twenty-six bus systems after compensation

Bus No	Voltage magnitude (KV)	Angle (degrees)	Bus No	Voltage magnitude (KV)	Angle (degrees)
0	15.000000	0.0000	14	14.763303	-0.8999
1	14.952262	-0.1835	15	14.749743	-0.9517
2	14.813057	-0.7392	16	14.741232	-0.9961
3	14.757295	-1.0052	17	14.737934	-1.0456
4	14.687941	-1.3918	18	14.731740	-1.0497
5	14.676061	-1.5160	19	14.778458	-0.8471
6	14.670671	-1.6360	20	14.753444	-1.0078
7	14.647491	-1.6523	21	14.675224	-1.4005
8	14.632035	-1.6633	22	14.670109	-1.4040
9	14.620444	-1.6715	23	14.667347	-1.4059
10	14.614647	-1.6756	24	14.666324	-1.4066
11	14.951236	-0.1841	25	14.668267	-1.4053
12	14.796676	-0.7882	26	14.625595	-1.6678
13	14.778919	-0.8468			
<i>Total power loss</i>					
<i>Active power loss= 73.306505 KW</i>					
<i>Reactive power loss= 74.492958 Kvar</i>					

The total active and reactive power loss savings due to shunt capacitor installation in the primary distribution feeder at node 6 and 17 is 37.201023 KW and 37.803117 Kvar respectively. Losses in each branch after compensation are reduced due to the capacitor placement. The loss reduction is explicitly shown in Figure 6-2 which is plotted the branch loss before and after compensation.

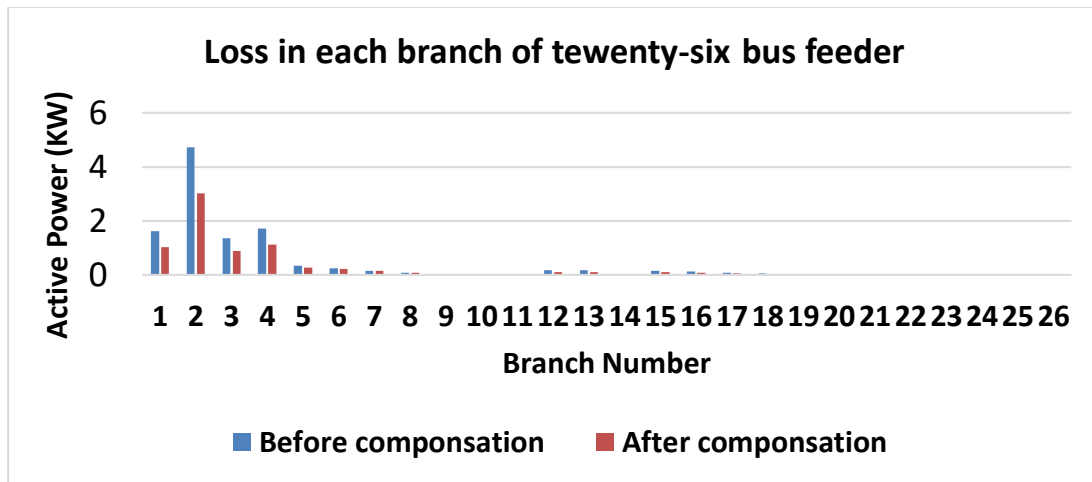


Figure 6-2 Loss of each branch reduced

6.1.3. Determining switched capacitors

For eighty-two bus nodes it was determined that nodes 8, 23 and 41 are the most suitable location for capacitor placement. The load factor of buses 23 and 41 are 0.61 and 0.63 respectively, therefore these nodes quantify to have both switched and fixed capacitors. The switched capacitor sizes are 300 Kvar and 1,000 Kvar for node 23 and 41 respectively and the remaining 1,500 Kvar are fixed values. For twenty-six-bus system the load factor for nodes 17 is 0.82. Therefore, this node quantifies to have a fixed capacitor 1750 Kvar and 850 Kvar at node 6.

6.2. Explanation on Savings and Socio-Economic Benefits of the Results

It is expected that the use of electricity generated by hydro power and diesel generators system in both urban and rural areas would improve quality life of the households; through improving social services in healthy, education and water, agro-industry and other income generating activities. But due to economic and technical challenges, Ethiopia Electric Power Corporation does not fulfil the demand of electric power. Hence, to fulfil the gap, a considerable effort should be done to minimize the losses in distribution of powers for further uses both in the utility and consumer sides.

In section 6.1 the analysis and results on two different feeders were given. A considerable percentage improvement in electric loss reduction is observed. The detailed explanation in Kwh savings and the socio-economic benefits that will be obtained based on the results in section 6.1 are given in this section.

6.2.1. Eighty-Two Bus Feeder

The power loss in the distribution feeder is directly proportional to the length of the feeder line. Longer distance distribution feeders have considerably large power loss woldia-II feeder is 73.673 km long. From Table 6-1 and 6-3 the total active and reactive power losses before compensation were found 402.4570 KW and 408.9708 Kvar and after compensation it becomes 158.4373 KW and 170.4254 Kvar respectively under the given load condition. It is clear that 244.0197 KW active powers and 238.5454 Kvar reactive powers are saved after loss optimization.

The annual total electric energy saving due to optimization of primary distribution feeder loss taking quarter of the 24 hours is about 534.403220 Mwh. With an average load factor of the feeder 0.73 the actual energy that can be commercialized is 390.1144 Mwh. It is clear that it is a significant number. With an average monthly consumption of a residence be 150 Kwh, more than 2,600 households can be electrified.

Financially about 142,683.00birr per annul will be collected assuming flat billing of 0.376 Birr/Kwh. Assuming fixed and switched capacitor of 2,800 Kvar investment cost is 191.10Birr/Kvar, then the cost of the capacitor will be 535,080.00 Birr. The payback period for the capacitor cost will be 4years

6.2.2. Twenty-Six Bus Feeder

From Table 6-4 and 6-6 the total loss before compensation was 110.5075 KW active powers and 112.2961Kvar reactive powers and after compensation it becomes 73.3065 KW and 74.4930 Kvar respectively under the given load condition, which after loss optimization the feeder loss reduces to 37.2010 KW active powers and 37.8031 Kvar reactive powers. Due to placement of 2,600 Kvar capacitors which costs 496,860.00 birr, 37.2010 KW and 37.8031 Kvar power is saved, assuming cost of capacitor is 191.10 Birr/Kvar.

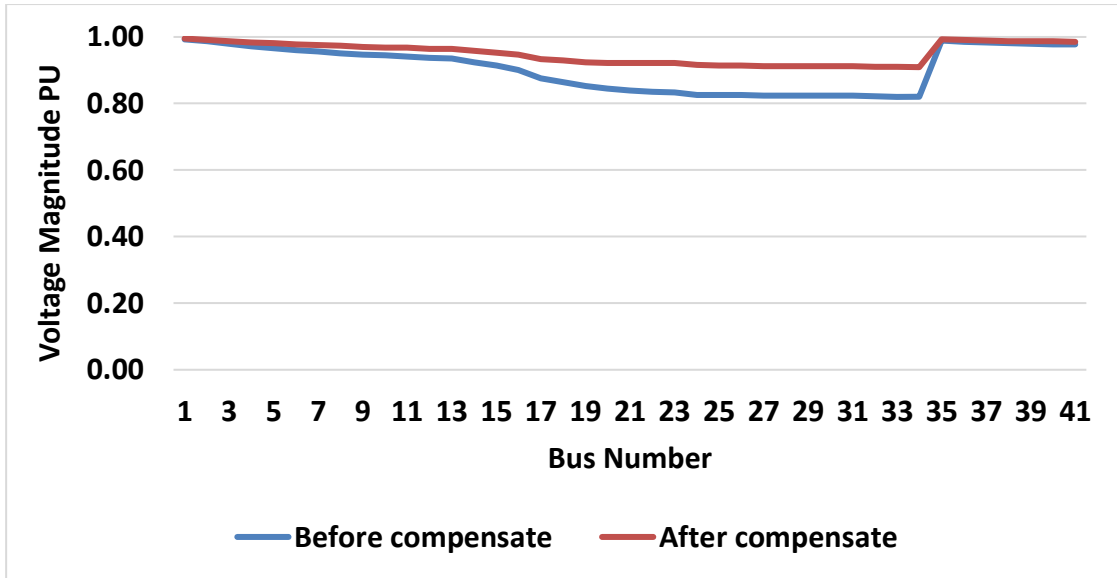
The annual total electric energy saving due to optimization of primary distribution feeder loss taking quarter of the 24 hours is about 81.470240 Mwh. with an average load factor 0.75; the actual energy that can be commercialized becomes 61.1027Mwh. With an average monthly consumption of a residence be 150 Kwh, more than 407 households can be electrified. Financially about 22,974.61Birr per year will be collected assuming flat billing of 0.376 Birr/Kwh and the payback period will be 21 years.

6.3. Voltage Profile

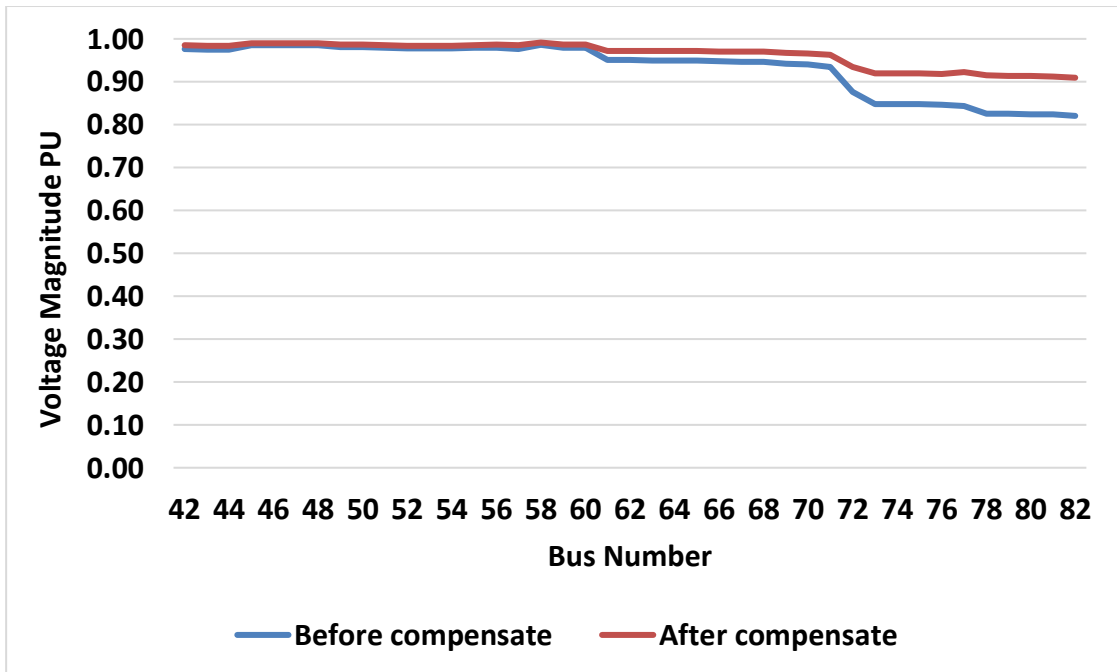
Capacitor placement in the primary distribution feeder, besides optimization of feeder loss will also improve the voltage regulation of the system. It is usually convenient to discuss distribution feeder voltage regulation in terms of voltage profiles of the feeder, because the voltages are everywhere different on the feeder. A profile simply indicates the feeder voltage magnitude versus location on the feeder. One of the factors that determine the quality of power supply is maintaining the sender voltage and the receiver voltage as closer as possible. In order to achieve this, practically different compensating devices are placed along the distribution system. Among them is capacitor placement. In this thesis, it is illustrated using the eighty-two-bus and twenty-six bus feeders.

6.3.1. Eighty-Two -Bus Feeder Voltage Profile

Considering Tables 6-1 and 6-3 the voltages at each node decreases as one move from the reference node to the last node, due to the voltage drop in the line. The capacitor produces a voltage rise because of its leading current flowing through the inductive reactance of the feeder. This capacitor improves the voltage level at each node which is shown in Figure 6-3 below



A



B

Figure 6-3 Voltage profile of eighty-two bus feeder before and after compensation

From Figure 6-3, it is clearly observed that the voltage profile is improved after the selected node is compensated. The minimum node voltage after compensation is 0.909383942 Pu and 0.820438585 Pu before compensation. Its voltage regulation improves from 10.84 % to 0.2727 %.

6.3.2. Voltage Profile of Twenty-Six Bus Feeder

The node voltages of the distribution feeder prior to and following loss optimization for twenty-six bus system considered in section 6.1.2. of Table 6-4 and 6-6 are given in Figure 6-4. Comparing the graphs in the figure, it is clearly seen that the branch voltage drop decreases hence the voltage profile of the nodes improves after the feeder is compensated.

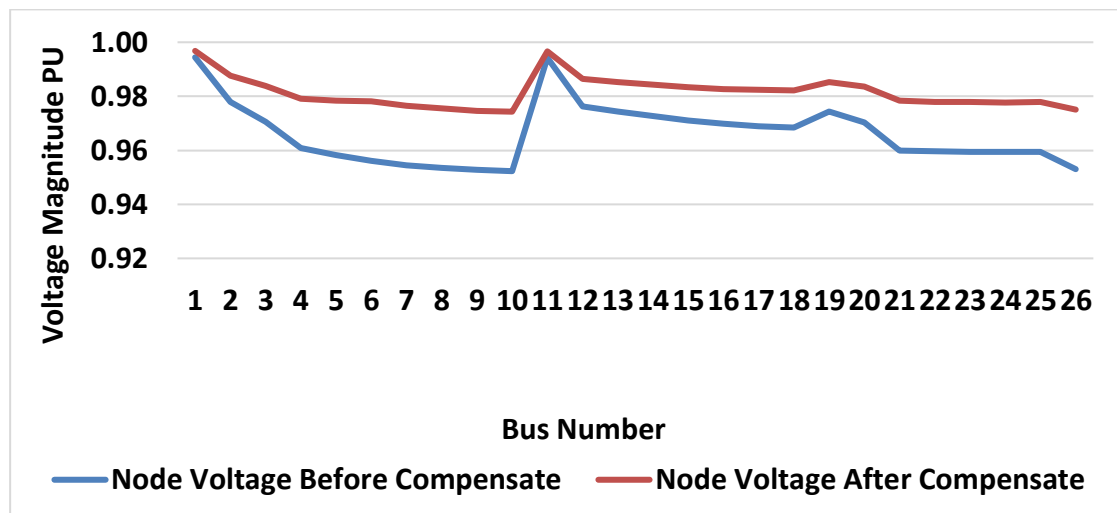


Figure 6-4 Voltage profile of twenty-six bus feeder before and after compensation

6.4. Summary of the Result

From Figure 6-1 the minimum node voltage before compensation is 0.952281Pu and 0.974309 Pu after compensation and its maximum voltage regulation improves from 4.43% to 2.31%. Therefore, it is concluded that due to capacitor placement the voltage profile and hence the voltage regulation of the system is improved. The results of the previous sections can be summarized shortly as follows in the following tables

Table 6-7 Eighty-Two Bus System

Description	Without compensation	With compensation
Total capacitor required (Kvar)		2,800.00
Total line current (A)	511.658622	411.594490
Released line current (A)		100.064132
Total reactive power demand (Kvar)	4,593.000000	4,422.574559
Total release reactive power (Kvar)		170.425441
Minimum voltage (Pu)	0.820302	0.909250
Voltage regulation (%)	21.01	9.47
Improvement of voltage regulation (%)		11.54
Total loss (KW)	402.457046	158.437311
Total loss reduction (%)		60.63
Total demand (KW)	6,124.000000	5,965.562689
Total released demand (KW)		158.437311
Total feeder capacity (KVA)	7,655.000000	7,426.109609
Total released feeder capacity(KVA)		232.695536

Table 6-8 Twenty-Six Bus Feeder

Description	Without compensation	With compensation
Total capacitor required (Kvar)		2600
Total line current (A)	271.462874	217.138062
Released line current (A)		54.324812
Total reactive power demand (Kvar)	2445.035000	2370.542042
Total release reactive power (Kvar)		74.492958
Minimum voltage (Pu)	0.952282	0.974310
Voltage regulation (%)	4.43	2.31
Improvement of voltage regulation (%)		2.31
Total loss (KW)	110.507528	73.306505
Total loss reduction (%)		33.66
Total demand (KW)	3260.000000	3186.693495
Total released demand (KW)		73.306505
Total feeder capacity (KVA)	4075.021000	3971.710589
Total released feeder capacity(KVA)		104.513370

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusion

Improving the performance of distribution networks by placing shunt capacitor in radial distribution system to reduce the loss written in this thesis is successfully achieving the goals set. Optimum capacitor placement in a distribution system, which essentially includes the optimal location and size of capacitors, is required to minimize the losses associated with the reactive component of branch currents. The location of capacitors is identified through optimizing the losses, which caused by the reactive component of branch currents obtained from the load flow solutions, by placing a capacitor at each node. The optimal capacitor size at each selected location is determined through optimizing of the loss saving equations with respect to the capacitor currents for multiple nodes identified for capacitor placement. The fixed and switched capacitor sizes are determined based on the load factor.

In Woldia distribution networks Eighty-two bus and twenty-six bus distribution system are considered for optimal capacitor placement to minimize the distribution feeder loss that caused by the reactive component of branch currents, in turn to improve the network performance. The result shows that the power loss before and after compensation is 402.4571 KW and 158.4373 KW the reduction of 60.63 % of the total loss for eighty-two bus and similarly the power loss before and after compensation is 110.5075 KW and 73.3065 KW the reduction of 33.66 % of the total loss for twenty-six bus system. In addition to voltage regulation improvement, the total feeder capacity is released by 232.6956 KVA and 104.5134 KVA for eighty-two bus and twenty-six systems respectively.

Reduction of reactive current flow by installing shunt capacitors in the primary distribution system releases the generation, substation capacities and reduces the transmission and distribution line losses as a result improve the performance of the system. Regarding the voltage profile, loss minimization using shunt capacitors reduces the current flows in each section of the feeder and hence the voltage drop in the section reduced. Therefore, the voltage profile is improved after the feeder line is compensated and the quality of the supply is improved.

7.2. Recommendation

In the present energy crises implementing energy loss reduction techniques has a paramount effect in the development of the country socially and economically. EEU or EEP is recommended to implement different loss minimization techniques. Capacitor for loss minimizations has a relatively low cost, simple in maintainer and shorter return period than other methods, and it is advisable to use this method in conjunction with natural compensation methods such as phase balancing. Distribution feeders having short length had lower loss despite of higher reactive current flow. Therefore, it is recommended to compensate the high reactive power flow by the consumers rather than the utilities. While the length greater than 30 km the compensated by utilities.

For best accuracy, optimization of the size, location, cost of capacitor and installation is very important, and this will be done using one of artificial methods like genetic algorithms in considering the discrete capacitor values rather than the continuous one.

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APPENDIX A: DERIVATION OF MODIFIED CARSON'S EQUATION

Carson's equations

In his paper, Carson assumes the earth is an infinite, uniform solid with a flat uniform upper surface and a constant resistivity. Any end effects introduced at the neutral grounding points are not large at power frequency, and are therefore neglected.

Carson made use of conductor images; that is every conductor at a given distance above ground has an image conductor the same distance below ground.

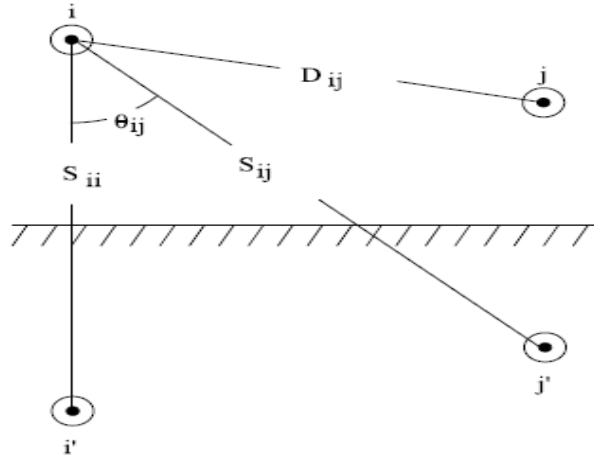


Figure A- 1conductors and images

Self-impedance of conductor i :

$$z_{ii} = r_i + 4wP_{ii}G + j (x_i + 2wG \ln \frac{S_{ii}}{RD_i} + 4wQ_{ii}G) \Omega / mile \quad \text{A- 1}$$

Mutual impedance between i and j :

$$z_{ij} = 4wP_{ij}G + j (2wG \ln \frac{S_{ij}}{D_{ij}} + 4wQ_{ij}G) \Omega / mile \quad \text{A-2}$$

Where r_i =resistance of conductor i in $\Omega / mile$

w =angular frequency, $f=50\text{Hz}$

$G = 0.1609344 \times 10^{-3} \Omega / mile$

S_{ij} =Distance between conductor i and j in feet

Q_{ij} = Angle between a pair of lines drawn from conductor i to its own image and to the image of conductor j

$$x_i = 2\omega G \ln \frac{RD_i}{GMR_i} \quad \Omega / \text{mile} \quad \text{A-3}$$

$$p_{ij} = \frac{\pi}{8} - \frac{1}{3\sqrt{2}} K_{ij} \cos(\theta_{ij}) + \frac{K_{ij}^2}{16} \cos(2\theta_{ij}) \cdot (0.6728 + \ln \frac{2}{K_{ij}}) \quad \text{A-4}$$

$$Q_{ij} = -0.0386 + \frac{1}{2} \ln \frac{2}{k_{ij}} + \frac{1}{3\sqrt{2}} k_{ij} \cos(\theta_{ij}) \quad \text{A-5}$$

$$K_{ij} = 8.565 \times 10^{-4} \cdot S_{ij} \cdot \sqrt{\frac{f}{\rho}} \quad \text{A-6}$$

Modified Carson's equations

Only two approximations are made in deriving the modified Carson's equations. These approximations involve the terms associated with P_{ij} and Q_{ij} .

$$P_{ij} = \pi/8 \quad \text{A- 7}$$

$$Q_{ij} = -0.03860 + \frac{1}{2} \ln \frac{2}{K_{ij}} \quad \text{A- 8}$$

Substituting equation (A-6) in to equation (A-8)

$$Q_{ij} = 3.8393 - \frac{1}{2} \ln S_{ij} + \frac{1}{4} \ln \frac{\rho}{f} \quad \text{A- 9}$$

$$\text{or } 2Q_{ij} = 7.6786 - \ln S_{ij} + \frac{1}{2} \ln \frac{\rho}{f}$$

Substituting equation (A-3) in to equation (A-1)

$$z_{ii} = r_i + 4\omega P_{ii} G + j (2\omega G \ln \frac{RD_i}{GMR_i} + 2\omega G \ln \frac{S_{ii}}{RD_i} + 4\omega Q_{ii} G) \Omega / \text{mile}$$

$$= r_i + 4\omega p_{ii} G + j 2\omega G (\ln \frac{S_{ii}}{GMR_i} + 2Q_{ii}) \quad \text{A-10}$$

substituting for $2Q_{ii}$

$$z_{ii} = r_i + 4\omega p_{ii} G + j 2\omega G (\ln \frac{1}{GMR_i} + 7.6786 - \frac{1}{2} \ln \frac{\rho}{f}) \quad \Omega / \text{mile}$$

Converting to Ω/km

$$\begin{aligned}
 p_{ii} &= \frac{\pi}{8} \\
 G &= 10^{-4} \quad \Omega/km \\
 \omega &= 2\pi f, \quad f = 50 \text{ HZ} \\
 \rho &= 100 \Omega - m \\
 r_i &\text{ is resistance in } \Omega/km
 \end{aligned}
 \tag{A-11}$$

Substituting equation (A-11) in to the last equation of (A-10) we obtained:

$$z_{ii} = r_i + 0.049348 + j 0.062832 \left(\ln \frac{1}{GMR_i} + 6.837026 \right) \Omega/km \tag{A-12}$$

Simplifying equation (A-2), we obtained:

$$\begin{aligned}
 z_{ij} &= 4\omega P_{ij} G + j 2\omega G \left(\ln \frac{S_{ij}}{D_{ij}} + 2Q_{ij} \right) \Omega/mile \\
 &= 4\omega p_{ij} G + j 2\omega G \left(\ln \frac{1}{D_{ij}} + 7.6786 + \frac{1}{2} \ln \frac{\rho}{f} \right)
 \end{aligned}
 \tag{A-13}$$

Substituting the values in equation (A-11), equation (A-13) becomes

$$z_{ij} = 0.049348 + j 0.062832 \left(\ln \frac{1}{D_{ij}} + 6.837026 \right) \Omega/km \tag{A-14}$$

Equations (A-12) and (A-14) are final modified Carson's equations in Ω/km

Where GMR_i and D_{ij} are given in meters

APPENDIX B: LINE IMPEDANCE CALCULATIONS

B-1 Overhead Lines

From Figure 4-3 and Table 4-1 applying equations 3-5 and 3-6, results

AAC-70

The self-impedance for phase conductors is:

$$\begin{aligned} z_{aa} &= r_a + 0.049348 + j0.062832 \left(\ln \frac{1}{GMR_a} + 6.837026 \right) \Omega / km \\ &= 0.4372 + 0.049348 + j0.062832 \left(\ln \frac{1}{0.003468} + 6.837026 \right) \\ &= (0.486548 + j0.785476) \Omega / km \\ z_{aa} &= z_{bb} = z_{cc} \end{aligned}$$

Applying equation 3-6 for the mutual impedance between phases a and b, phase a and c, phase b and c.

$$\begin{aligned} z_{ab} &= 0.049348 + j0.062832 \left(\ln \frac{1}{D_{ab}} + 6.837026 \right) \Omega / km \\ &= 0.049348 + j0.062832 \left(\ln \frac{1}{0.6} + 6.837026 \right) \\ &= (0.049348 + j0.461680) \Omega / km \end{aligned}$$

$$\begin{aligned} z_{ac} &= 0.049348 + j0.062832 \left(\ln \frac{1}{D_{ac}} + 6.837026 \right) \Omega / km \\ &= 0.049348 + j0.062832 \left(\ln \frac{1}{1.05} + 6.837026 \right) \\ &= (0.049348 + j0.426518) \Omega / km \end{aligned}$$

$$\begin{aligned} z_{bc} &= 0.049348 + j0.062832 \left(\ln \frac{1}{D_{bc}} + 6.837026 \right) \Omega / km \\ &= 0.049348 + j0.062832 \left(\ln \frac{1}{0.45} + 6.837026 \right) \\ &= (0.049348 + j0.479756) \Omega / km \end{aligned}$$

The positive sequence impedance is obtained using equations 3-10 up to 3-13

Applying equation 3-9 the self-impedance is

$$z_s = \frac{1}{3}(z_{aa} + z_{bb} + z_{cc})\Omega / km$$

$$= (0.486548 + j0.785476)\Omega / km$$

$$z_m = \frac{1}{3}(z_{ab} + z_{bc} + z_{ca})\Omega / km$$

$$= \frac{1}{3}(0.148044 + j1.367954)$$

$$= (0.049348 + j0.455985)\Omega / km$$

The positive sequence impedance z_+ of AAC-70 is obtained using equation 3-12 as:

$$z_+ = z_s - z_m\Omega / km$$

$$= (0.4372 + j0.444276)\Omega / km$$

The line segments positive sequence impedances are obtained by multiplying the impedance per kilometre by its length as tabulated in Table B-1 and B-2.

Table B- 1 Eighty-two bus overhead conductor line and load data

Bus No	Sending node	Receiving node	Conductor type	Length (km)	Resistance (Ω)	Reactance (Ω)	Receiving end load	
							Real power (kW)	Reactive power (Kvar)
1	0	1	AAC-70	0.350	0.153020	0.155497		
2	1	2	AAC-70	0.450	0.196740	0.199924		
3	2	3	AAC-70	0.500	0.218600	0.222138		
4	3	4	AAC-70	0.500	0.218600	0.222138	160	120
5	4	5	AAC-70	0.500	0.218600	0.222138	40	30
6	5	6	AAC-70	0.450	0.196740	0.199924	252	189
7	6	7	AAC-70	0.350	0.153020	0.155497	252	189
8	7	8	AAC-70	0.450	0.196740	0.199924		
9	8	9	AAC-70	0.400	0.174880	0.177710		
10	9	10	AAC-70	0.350	0.153020	0.155497	160	120
11	10	11	AAC-70	0.400	0.174880	0.177710		
12	11	12	AAC-70	0.500	0.218600	0.222138	80	60
13	12	13	AAC-70	0.500	0.218600	0.222138		
14	13	14	AAC-70	1.500	0.655800	0.666414	80	60
15	14	15	AAC-70	1.500	0.655800	0.666414	40	30
16	15	16	AAC-70	2.000	0.874400	0.888552	40	30

17	16	17	AAC-70	4.000	1.748800	1.777104		
18	17	18	AAC-70	2.000	0.874400	0.888552	160	120
19	18	19	AAC-70	2.000	0.874400	0.888552		
20	19	20	AAC-70	2.000	0.874400	0.888552		
21	20	21	AAC-70	1.000	0.437200	0.444276	80	60
22	21	22	AAC-70	1.000	0.437200	0.444276	80	60
23	22	23	AAC-70	1.000	0.437200	0.444276	160	120
24	23	24	AAC-70	2.000	0.874400	0.888552		
25	24	25	AAC-70	0.420	0.183624	0.186596		
26	25	26	AAC-70	0.253	0.110612	0.112402	120	90
27	26	27	AAC-70	0.200	0.087440	0.088855		
28	27	28	AAC-70	0.200	0.087440	0.088855	80	60
29	28	29	AAC-70	0.250	0.109300	0.111069	40	30
30	29	30	AAC-70	0.300	0.131160	0.133283	40	30
31	30	31	AAC-70	0.250	0.109300	0.111069	40	30
32	31	32	AAC-70	2.000	0.874400	0.888552	160	120
33	32	33	AAC-70	2.000	0.874400	0.888552		
34	33	34	AAC-70	1.000	0.437200	0.444276	80	60
35	1	35	AAC-70	0.500	0.218600	0.222138	160	120
36	35	36	AAC-70	0.550	0.240460	0.244352		
37	36	37	AAC-70	0.500	0.218600	0.222138		
38	37	38	AAC-70	0.450	0.196740	0.199924	252	189
39	38	39	AAC-70	0.500	0.218600	0.222138		
40	39	40	AAC-70	0.500	0.218600	0.222138	80	60
41	40	41	AAC-70	0.450	0.196740	0.199924	252	189
42	41	42	AAC-70	0.450	0.196740	0.199924		
43	42	43	AAC-70	0.400	0.174880	0.177710	252	189
44	43	44	AAC-70	0.500	0.218600	0.222138	252	189
45	36	45	AAC-70	0.500	0.218600	0.222138	160	120
46	45	46	AAC-70	0.500	0.218600	0.222138		
47	46	47	AAC-70	0.500	0.218600	0.222138	80	60
48	46	48	AAC-70	0.500	0.218600	0.222138	40	30
49	37	49	AAC-70	1.500	0.655800	0.666414	160	120
50	49	50	AAC-70	0.500	0.218600	0.222138	80	60
51	50	51	AAC-70	2.000	0.874400	0.888552		
52	51	52	AAC-70	2.500	1.093000	1.110690	80	60
53	52	53	AAC-70	1.550	0.677660	0.688628	40	30
54	53	54	AAC-70	1.350	0.590220	0.599773	20	15
55	51	55	AAC-70	0.500	0.218600	0.222138	20	15

56	39	56	AAC-70	0.500	0.218600	0.222138	20	15
57	42	57	AAC-70	0.520	0.227344	0.231024	80	60
58	2	58	AAC-70	0.570	0.249204	0.253237	80	60
59	3	59	AAC-70	0.500	0.218600	0.222138	40	30
60	59	60	AAC-70	0.450	0.196740	0.199924	80	60
61	8	61	AAC-70	0.500	0.218600	0.222138		
62	61	62	AAC-70	0.500	0.218600	0.222138		
63	62	63	AAC-70	0.500	0.218600	0.222138	80	60
64	61	64	AAC-70	0.500	0.218600	0.222138	252	189
65	62	65	AAC-70	0.500	0.218600	0.222138	160	120
66	9	66	AAC-70	0.500	0.218600	0.222138	160	120
67	66	67	AAC-70	0.500	0.218600	0.222138	80	60
68	67	68	AAC-70	0.500	0.218600	0.222138	20	15
69	11	69	AAC-70	0.500	0.218600	0.222138	40	30
70	69	70	AAC-70	0.500	0.218600	0.222138	160	120
71	13	71	AAC-70	1.500	0.655800	0.666414	20	15
72	17	72	AAC-70	1.250	0.546500	0.555345	80	60
73	19	73	AAC-70	4.000	1.748800	1.777104	80	60
74	73	74	AAC-70	1.000	0.437200	0.444276		
75	74	75	AAC-70	1.000	0.437200	0.444276	80	60
76	74	76	AAC-70	2.000	0.874400	0.888552	160	120
77	20	77	AAC-70	0.520	0.227344	0.231024	80	60
78	24	78	AAC-70	1.320	0.577104	0.586444	40	30
79	26	79	AAC-70	1.000	0.437200	0.444276	120	90
80	27	80	AAC-70	0.570	0.249204	0.253237	80	60
81	80	81	AAC-70	0.700	0.306040	0.310993	40	30
82	33	82	AAC-70	2.000	0.874400	0.888552	20	15

Table B- 2 Twenty-six bus overhead conductor line and load data

Bus No	Sending node	Receiving node	Conductor type	Length (km)	Resistance (Ω)	Reactance (Ω)	Receiving end load	
							Real power (kW)	Reactive power (Kvar)
1	0	1	AAC-70	0.5000	0.218600	0.222138		
2	1	2	AAC-70	1.5000	0.655800	0.666414		
3	2	3	AAC-70	1.0000	0.437200	0.444276		
4	3	4	AAC-70	1.4700	0.642684	0.653086		
5	4	5	AAC-70	0.5000	0.218600	0.222138	252	189
6	5	6	AAC-70	0.5000	0.218600	0.222138	252	189
7	6	7	AAC-70	0.4500	0.196740	0.199924	252	189
8	7	8	AAC-70	0.4000	0.174880	0.177710		
9	8	9	AAC-70	0.4500	0.196740	0.199924	252	189
10	9	10	AAC-70	0.4500	0.196740	0.199924	252	189
11	1	11	AAC-70	0.5000	0.218600	0.222138	40	30
12	2	12	AAC-70	0.4500	0.196740	0.199924	80	60
13	12	13	AAC-70	0.5500	0.240460	0.244352		
14	13	14	AAC-70	0.5000	0.218600	0.222138	80	60
15	14	15	AAC-70	0.5000	0.218600	0.222138	160	120
16	15	16	AAC-70	0.4500	0.196740	0.199924	252	189
17	16	17	AAC-70	0.5500	0.240460	0.244352	252	189
18	17	18	AAC-70	0.4800	0.209856	0.213252	252	189
19	13	19	AAC-70	0.4500	0.196740	0.199924	20	15
20	3	20	AAC-70	0.4700	0.205484	0.208810	160	120
21	4	21	AAC-70	0.5500	0.240460	0.244352	252	189
22	21	22	AAC-70	0.5000	0.218600	0.222138		
23	22	23	AAC-70	0.4500	0.196740	0.199924	80	60
24	23	24	AAC-70	0.5000	0.218600	0.222138	40	30
25	22	25	AAC-70	0.4500	0.196740	0.199924	80	60
26	8	26	AAC-70	0.5000	0.218600	0.222138	252	189

Since the line is short, the shunt admittance of overhead lines is neglected.

APPENDIX C: APPROXIMATE LOSS SAVING

Maximum loss saving due to the supply of reactive component of current using shunt capacitor at each node and the respective capacitor size is obtained by using equations 6-8 up to 6-10. The results are as given in Table C-1

Table C- 1 Loss saving and capacitor size obtained after node 23 is compensated

Bus No	Loss savings (KW)	Capacitor size (Kvar)	Bus No	Loss savings (KW)	Capacitor size (Kvar)
1	0.249089	65.47	42	8.495408	991.68
2	6.813498	2070.37	43	8.318736	937.49
3	5.350573	1824.72	44	7.832630	864.02
4	10.399672	1687.06	45	5.730010	1229.51
5	11.801354	1581.92	46	4.710375	991.66
6	13.031848	1513.50	47	3.995814	830.77
7	13.626649	1453.06	48	3.946877	825.73
8	13.966405	1369.62	49	4.566027	817.69
9	13.555251	1275.86	50	3.896522	705.16
10	12.954980	1193.14	51	3.036594	505.55
11	11.661120	877.43	52	2.517423	385.31
12	11.065787	998.64	53	2.216076	332.06
13	10.041104	906.80	54	1.974854	294.12
14	7.756401	704.99	55	2.813205	467.19
15	6.063804	564.00	56	7.088346	1024.17
16	4.455003	432.91	57	7.679253	889.84
17	2.469136	271.38	58	4.142829	1219.54
18	1.757487	213.54	59	6.515991	1342.16
19	1.074791	157.06	60	5.327996	1085.39
20	0.400652	90.94	61	13.152776	1243.29
21	0.183330	60.03	62	12.113357	1125.21
22	0.046481	29.54	63	11.037316	1019.37
23			64	12.133836	1126.14
24	0.134156	46.84	65	11.161310	1024.93
25	0.188073	54.94	66	12.483233	1153.01
26	0.215321	58.91	67	11.380263	1043.63
27	0.239424	61.39	68	10.365017	949.17
28	0.256064	63.23	69	11.309967	1011.39
29	0.273274	65.00	70	10.544146	932.47

30	0.291872	66.78	71	8.015254	720.78
31	0.305493	67.99	72	2.355294	254.36
32	0.401443	75.11	73	1.492639	167.20
33	0.423035	74.56	74	1.555566	166.90
34	0.450219	73.91	75	1.533991	162.30
35	6.030379	1892.92	76	1.596945	162.20
36	7.101985	1595.39	77	0.402728	90.03
37	7.661084	1418.79	78	0.143227	47.18
38	8.139733	1312.55	79	0.202224	55.89
39	8.296203	1201.30	80	0.244610	61.63
40	8.515314	1120.78	81	0.243881	60.75
41	8.652596	1059.38	82	0.406990	70.91
<i>The maximum loss saving is obtained at node 8</i>					

Table C- 2 Loss saving and capacitor size obtained after node 23 and 8 is compensated

Bus No	Loss savings (KW)	Capacitor size (Kvar)	Bus No	Loss savings (KW)	Capacitor size (Kvar)
1	0.060792	32.37	42	6.645225	833.66
2	0.698246	664.29	43	6.564772	770.33
3	0.289954	426.37	44	6.213428	971.71
4	0.316819	296.00	45	3.571877	787.63
5	0.181756	197.64	46	2.965553	661.95
6	0.102300	135.18	47	2.531795	656.89
7	0.039319	78.77	48	2.492872	674.25
8			49	3.098343	580.13
9	0.019069	48.36	50	2.631907	423.04
10	0.041180	67.99	51	2.121929	327.45
11	0.046376	111.21	52	1.814498	283.23
12	0.056655	72.22	53	1.609080	251.13
13	0.047889	63.30	54	1.436906	391.12
14	0.025699	41.02	55	1.967730	879.10
15	0.005583	17.30	56	5.211995	788.53
16	0.001796	8.79	57	6.018103	788.53
17	0.070530	46.40	58	0.461409	407.41
18	0.158181	64.81	59	0.397025	332.54
19	0.350385	90.74	60	0.346531	277.84
20	0.837237	133.03	61	0.016140	44.01
21	1.174446	153.76	62	0.031925	58.38

22	1.594205	175.07	63	0.035423	58.36
23			64	0.032984	59.34
24	1.046500	132.42	65	0.042774	64.12
25	0.891836	121.10	66	0.037838	64.16
26	0.804523	115.27	67	0.043234	65.01
27	0.769021	111.37	68	0.041063	60.38
28	0.731208	108.16	69	0.075364	83.45
29	0.692337	100.98	70	0.088352	86.27
30	0.651433	98.18	71	0.042601	53.12
31	0.621780	79.38	72	0.052340	38.36
32	0.437584	69.98	73	0.065780	35.52
33	0.363603	66.14	74	0.039787	27.01
34	0.316525	1313.61	75	0.031883	23.68
35	2.898344	1245.27	76	0.015764	16.31
36	4.318260	1161.71	77	0.799745	128.39
37	5.125983	1105.25	78	0.953447	123.22
38	5.760078	1030.78	79	0.814877	113.55
39	6.095762	976.04	80	0.744351	108.83
40	6.444924	932.02	81	0.716031	105.37
41	6.683709	877.95	82	0.333554	64.99
<i>The maximum loss saving is obtained at node 41</i>					

Table C- 3 Loss saving and capacitor size obtained after node 6 is compensated

Bus No	Loss savings (KW)	Capacitor size (Kvar)	Bus No	Loss savings (KW)	Capacitor size (Kvar)
1	0.042122	32.45	14	2.515506	694.39
2	1.688826	649.27	15	2.973371	690.61
3	0.853839	375.52	16	3.238323	676.05
4	0.226251	157.61	17	3.298153	641.68
5	0.064699	79.87	18	3.151820	601.37
6			19	1.618294	530.77
7	0.037514	55.61	20	0.812494	340.51
8	0.098103	86.95	21	0.319051	176.46
9	0.500697	105.53	22	0.340070	173.67
10	0.180972	110.36	23	0.340883	167.17
11	0.246067	354.47	24	0.323828	156.50
12	1.357796	677.56	25	0.331949	164.97
13	1.974430	689.35	26	0.123873	94.01
<i>The maximum loss saving is obtained at node 17</i>					

