Power Loss Minimization in Distribution Networks Using PSO-Based Voltage and Reactive Power Control with D-STATCOM

Alemtsehay Ergete

A Thesis submitted to the

Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented In Partial Fulfillment of the Requirements for Degree Of

Master‘s In Electrical Power Engineering and Control Engineering

(Specialization in Power System Engineering)

Office of Graduate Studies

Adama Science and Technology University

Adama, Ethiopia

October, 2025

Power Loss Minimization in Distribution Networks Using PSO-Based Voltage and Reactive Power Control with D-STATCOM

(A Case Study Bote Town 33kv line Distribution system)

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Advisor: Dr.Negasa Muleta

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DECLARATION

I declare that this thesis entitled ― Power Loss Minimization in Distribution Networks Using PSO-Based Voltage and Reactive Power Control with D-STATCOM A Case Study of Bote town distribution system‖ is my own work and has not been submitted to any university for similar purpose. The references used in this thesis are duly recognized by proper citations.

Alemtsehay Ergete	____________________	_________________
Name of student	Signature	Date

RECOMMENDATION

II, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled ― Power Loss Minimization in Distribution Networks Using PSO-Based Voltage and Reactive Power Control with D-STATCOM (A Case Study of Bote town distribution system)‖ prepared under my guidance by Alemtsehay Ergete submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power and Control Engineering (Power System Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr.Negasa Muleta	______	______________
Advisor	Signature	Date

APPROVAL PAGE OF M.Sc. THESIS

I the advisor of thesis entitled ― Power Loss Minimization in Distribution Networks Using PSO-Based Voltage and Reactive Power Control with D-STATCOM (A Case Study of Bote town distribution system)‖ and developed by Alemtsehay Ergete, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr.Negasa Muleta ______

Advisor | Signature | Dat

We, the undersigned, members of the Board of Examiners of the thesis by Alemtsehay Ergete have read and evaluated the thesis entitled ― **Power Loss Minimization in Distribution Networks Using PSO-Based Voltage and Reactive Power Control with D-STATCOM (A Case Study of Bote town distribution system)**‖ and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering (Power Engineering).

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ACRONYMS

AC	Alternate current
DC	Direct current
IGBT	Insulated-gate bipolar transistor
GTO	Get turns off
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
PU	Per unit
IEC	International Electro technical Commission
IEEE	International of Electrical and Electronics Engineers
D-STATCOM	Distribution Static synchronous compensator
FACTS	Flexible AC Transmission System
VVC	Volt/Var Control
AVR	Automatic Voltage Regulator
PWM	Pulse with modulation
SVC	Static var Compensator
KVAR	Kilovolt Ampere Reactive
KVA	Kilovolt Ampere
MW	Mega watt
MVA	Mega volt Ampere
KV	Kilovolt
SSSC	Static Synchronous Series compensator
TCSC	Thyristor Controlled Series Compensator
UPFC	Unified Power Flow Controller
UPQC	Unified power quality control
MATLAB	Matrix Laboratory(software)
THD	Total Harmonic Distortion
LT	Lower Transmission

ABSTRACT

Energy consumption in Ethiopia is currently rising at a significant rate due to the country's rapidly expanding infrastructure and economy. One of the challenges is a reliable power supply with affordable energy prices and reduced CO2 emissions. Distribution feeders play a crucial role in transferring power from distribution substations to transformers near the customers' locations. However, certain issues such as low power factor, excessive loads, and long travel distances hinder their effectiveness in delivering electricity to connected customers. Voltage variations and under voltage are common problem for the Bote Town water pumping station, industries, commerce and residential end use. In this thesis, the radial distribution system's voltage profile is improved and power loss is minimized. By incorporating a D-STATCOM (Distributed Static Synchronous Compensator) into the Meki-Alemtena in order to solve these problems and enhance the voltage profile of distribution feeders The Bote town distribution feeder was used as an effective case study. Adametulu, Meki, Ziway, and Alemtena are all supplied with electricity via the Adametulu distribution substation's numerous outgoing feeds. The Meki-Alemtena feeder was selected as the test system among these feeders because of its lengthy route and heavy loads. This study compares the voltage profile and line losses (reactive power, active power) with and without a compensating device (D-STATCOM). The PSO optimization technique and forward/backward sweep load flow analysis were used to determine the optimal placement and dimensions of the compensation devices. Subsequently, simulation findings indicate that the reactive power loss decreases from 1374.5KVar to 126.5238KVar and the active power loss decreases from 2511.1KW to 229.0662KW. The results confirm an improvement, with active and reactive power losses reduced by 90.88% and 90.79% respectively, and the minimum voltage raised to 0.96266 p.u., which is within the lower IEEE voltage limit. It is reasonable to conclude that D-STATCOM (Distribution Static Compensator) should be implemented for electrical distribution systems, particularly when reactive power, voltage fluctuations, or power quality issues are present.

Keywords*: -D-STATCOM, PSO, MATLAB, Voltage profile improvement*

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CHAPTER ONE

1. INTRODUCTION

1.1 Background

It is true that an essential part of any power system that provides end customers with electrical energy is the electric power distribution system. It is located between the main substation and the local end user's meter terminal. Through the use of step-down transformers, the generated electrical power from the transmission network is stepped down to a lower voltage magnitude, usually between 2.4 and 33 kV. Distribution substations, feeders, distributors, transformers, and service mains are among the fundamental components that make up distribution systems. These components are employed in a variety of ways to categorize distinct distribution system types. A distribution system can be classified as either DC or AC according on its kind, and depending on its contraction, it can be classified as overhead or underground.(Yuan, H. Minyou and C., 1994). Despite being built to transmit electricity continuously and reliably, power distribution networks frequently encounter issues that cause service interruptions and have a detrimental effect on customers. These problems, which impact comfort, productivity, and economic stability in a variety of industries, can vary from power outages to voltage swings and harmonics. Power losses are unavoidable when power is delivered from the source to the customer and are defined as the difference between the total energy supplied to the network and the energy used by customers. The causes of power outages in distribution networks are usually divided into two primary categories: technical and non-technical losses. losses in the condactor caused by resistance in the cables and overhead wires, Technical losses include resistive losses in the lines that connect to customers in service lines, magnetic losses in the core and windings in transformers, losses in the measuring apparatus in KWH meters, etc. With enough attention, these losses can be reduced even though they cannot be totally prevented.losses from unmetered connections, unauthorized connections or meter tampering (Energy Theft), and distribution-related losses brought on by inaccurate billing or meter readings.Non-technical losses include things like .

There are numerous ways to reduce losses, including as distributed generation, VAR compensation, network reconfiguration, capacitor placement, and the installation of smart meters for non-technical losses. (Subiyanto, 2018).

Caused by a number of power quality problems, including as fluctuating frequencies, abnormally high or low voltages, fault-induced voltage imbalances, and high levels of total harmonic distortion (THD) in the current.Notwithstanding these problems, there are no generally recognized guidelines outlining the minimal dependability requirements for electricity. Voltage fluctuations and interruptions are two of these issues that are very harmful to the sector. When electricity is sent over long distances or over heavy loads, distribution networks experience voltage drop. The load current may lead the feeder to either provide or consume reactive power. Efficiency and power distribution are impacted by this problem. Feeders provide net reactive power when the load is below the surge impedance loading and absorb reactive power when the load is above the surge impedance loading. These things may contribute to this voltage drop issue.

Adametulu, Meki, Batu, Bulibula, and Bote town are among the regions served by the Adametulu distribution substation, which is a part of the Oromia Electric Utility's network. The Adametulu substation's low voltage feeders deal with issues such overloaded lines, frequent power outages, and low voltage at client locations. Customers face challenges and the quality of services is negatively impacted by these serious reliability problems in the electricity distribution system, especially when it comes to Bote Town's drinking water supply.

Utilizing cutting-edge electrical devices to boost power system efficiency with an emphasis on reducing power losses and increasing system stability. This include older Flexible AC Transmission Systems (FACTS) equipment like reactors and capacitor banks, as well as more recent models like the Unified Power Quality Controller, Distribution Static Compensator (D-STATCOM), and Static Synchronous Series Compensator (SSSC).They serve a number of functions, including as power flow optimization, reactive power compensation, and voltage management.

Compared to other reactive power compensation devices, D-STATCOM offers better features, such as low power losses, low harmonic output, exceptional regulating capabilities, affordability, and small size. (T. Yuvaraj, K. R. Devabalaji, and K. Ravi, 2015)

This has made distributed D-STATCOMs a more appealing option for compensating for lowering loss and increasing voltage.

1.2 Case Study Area Description

The research site is in the East part of the Main Ethiopian Rift, in east shoa zone of Oromia National State at 117 km from Addis Ababa.

Zone: East Shewa

Woreda: Lume

Region: Oromia

Location: 08.297848 N 38.948923E

Elevation: 1,460 m (4790 feet)

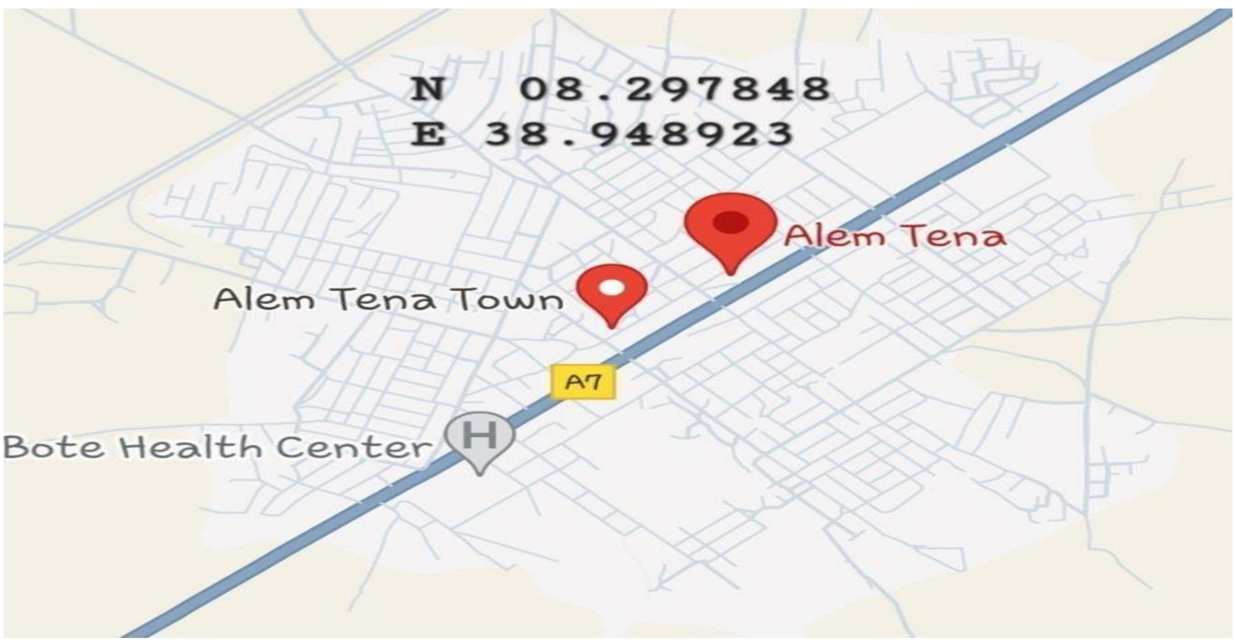

Figure 1.1 Location of the site (Bote Town) [Google map]

1.3 Statement of the Problem

The percentage of the population residing in urban areas is progressively and continuously increasing. As a result, residential, commercial, and industrial users' demands for electrical energy also increase. Large power losses are caused by the distribution networks' major problems, which include a high R/X ratio, extreme voltage drop, and feeder failures. These dependability problems make customer interactions more difficult and lower the caliber of services. The electricity distribution system's serious reliability problems make customer activities more difficult and result in poor service quality. The distribution feeders that transport electricity from the substation to the consumers are currently operating at capacity. Overloaded long-distance distribution feeders experience considerable losses and problems with voltage drop. For the Bote Town water pumping station, businesses, residential end users, and industry, voltage fluctuations and under voltage are frequent issues. For this reason, a scientific solution is needed to develop ways to minimize power loss in the voltage profile. Finding methods to reduce power loss and scientific answers to these issues are therefore essential. This thesis employs MATLAB-Simulink software and the Particle Swarm Optimization algorithm to optimize D-STATCOM allocation in order to minimize power loss in the Bote distribution system.Objectives

1.4 Objective

1.4.1 General Objective

To develop and implement a **PSO-based optimization approach** for voltage and reactive power control in distribution networks using D-STATCOM, with the aim of minimizing power losses and improving overall system performance.

1.1.2 Specific Objectives

The following specific aim of the research is to achieve the main objectives:

- T**o** analyze all the relevant data from the substation feeders.
- To model D-STATCOM for the Bote distribution network feeder.
- To apply Particle Swarm Optimization (PSO) for determining the optimal control settings of D-STATCOM for effective voltage regulation and reactive power compensation.
- Choose the ideal location and dimensions for D-STATCOM using the PSO method.
- To assess the system's performance with and without D-STATCOM

1.5 Scope and Limitation of the Study

The distribution feeder's voltage problem-minimizing options are examined using particle swarm optimization. MATLAB simulation tools will be used to simulate the proposed system, and the system's performance will be compared before and after modification.

1.6 Significance of the Study

Customers and the Ethiopian Electric Utility (EEU) both greatly value the thesis work's output. Furthermore, the following contributions will be included in the thesis output:.

- Its electrical power supply's voltage profile will be raised and power loss will be reduced.
- Its electric power system is more reliable.
- To show D-STATCOM is the best-compensating device for improving distribution system performance.

CHAPTER TWO

2. LITERATUREREVIEW

2.1 Electrical power distribution systems

The electrical power system's distribution system links the low voltage consumer service point to the high voltage transmission network.Any distribution system, feeders, distributors, and service mains are used to distribute power. enormous volumes of current are sent to feeder locations via feeders, which are enormous current-carrying cables. Distributors are conductors that enable current to be drawn from a supply and delivered to a customer's location. A service main is often a short cable that runs from the client to the distributor's terminals.

Electric power distribution is the process of delivering power coming from the transmission system to businesses, individual consumers, and other power-dependent infrastructure. Medium voltage power is provided to the customer's location mostly via primary distribution lines, which end at distribution transformers.The major distribution system for the electric distribution system is the connection between the distribution substation and distribution transformers. The circuits that provide power to the system are referred to as distribution feeders or secondary feeders. A standard power distribution feeder supplies power to the primary and secondary circuits.

A system of interconnected power lines that makes it easier to move electricity from power production facilities to final customers is known as an electrical grid. This network is made up of distribution lines that link to final customers, transmission cables with high voltage that carry electricity over great distances from distant sources to areas of demand, and power-generating stations that produce electricity. Power lines with high voltage travel via step-down transformers in substations, which lower the voltage so that it can be used. Low voltage power feeders are then used to split and distribute this voltage in various directions.(Desta, 2019)

2.2 Power Loss and Voltage Drop

The total electrical power losses in distribution systems are caused by a number of components, such as transformers, capacitors, insulators, and power losses in transmission and distribution lines.Reactive power losses and real power losses are the two categories into which these losses fall. Reactive power losses are brought on by reactive components in the system, whereas actual power losses are produced by line resistance.Reactive power losses are important, however utilities mostly concentrate on reducing actual power losses since they have an impact on the effectiveness of energy distribution. This is due to the fact that regulating the flow of reactive power at a particular level permits the flow of actual power, which is necessary to maintain the proper voltage level in the system.The distribution network completes the power system by connecting to end users. Both utilities and consumers are impacted by distribution network faults. One of these problems is voltage loss, which needs to be reduced in order to maintain appropriate voltage levels at load locations.When powering heavy loads or utilizing long-distance lateral radial feeders, voltage drop issues frequently occur. Finding a way to solve this issue and keep the voltage at different system nodes under control is therefore essential. In reality, "voltage control" relates to reactive power regulation since controlling reactive power and node voltages reduces power losses, a significant concern for utilities.A range of voltage-regulating devices, such as network reorganization, Distributed Generation (DG) deployment, Shunt/series capacitors, voltage regulators, and tap change transformers, and the addition of Devices for the Flexible AC Transmission System (FACTS), are installed in systems of distribution to increase voltage and control reactive power.(L.Ramesh, .P.Chowdhury and S.Chowdhury, 2009)

2.3 Factors Affecting Voltage Drop and Power Loss in Distribution System

Loss of distribution feeders and increasing voltage fluctuation in the distribution network are caused by several sources. The two main elements influencing a line's voltage drop are line impedance and current flowing through the wire. Consequently, as impedance or current increases, the voltage drop will also increase. The following list includes some of the known variables that either directly or indirectly impact voltage drop and distribution line losses. These factors must first be taken into account by an electric supplier that wants to reduce line losses.

- **Conductor poor joints and terminations:** Inadequate junctions and terminations are a major cause of the feeder's notable voltage dips. A loose connection between two interconnected wires results in poor joints and terminations. Heat is produced as a result of the considerable resistance this loose contact causes to the current flow. A voltage drop occurs at that specific place as a result of the resistance rising.(Reza Indra Satrio and Subiyanto, 2018)

- **Joint hot spots:** High resistance points originate from the formation of mechanically weak joints or terminations, which causes joint hot spots. Localized heating brought on by this high resistance encourages oxidation and creep. As a result, the link becomes less secure., which causes more heating until the contacts glow. At this point, as copper and aluminum's thermal resistance rises, a larger voltage loss is seen.
- **Using Under-Sized Conductors:** Electrical resistance measures the difficulty of pushing charges traveling through a conductor, whereas you can think of voltage as the force that pushes charges along a conductor.. For flowing currents, electrical resistance is similar to friction in relation to flow; longer, thinner cables offer greater resistance than shorter, thicker wires.

- **Using Non-Uniform Conductor Material:** Corrosion is an crucial element to consider while Choosing materials for conductors. The two forms of corrosion that most significantly impact on a metal's electrical properties are oxidation and galvanic corrosion. When selecting conductor metals, consideration should be given to galvanic corrosion, which is caused by an electrical potential difference between two or more metals.

- **Loads on the main feeder:** The loads attached to the downstream portion of the feeder dictate the currents in each feeder segment along its distribution feeder. Even when the feeder impedance is constant, the current influences the voltage variance.
- **Low voltage level:** Even slight variations in voltage can affect equipment efficiency and increase system losses since most residential and commercial loads are inductive. Low voltage levels also have an impact on how long electric devices last.(singh, 2018)
- Lengthy distribution lines: The series impedance of a feeder has a linearly inverse relationship with its length. Consequently, the feeder's length has a major impact on voltage variation

- **Location of Distribution transformer:** Energy losses in the system result from the distribution transformer's improper placement; for instance, consumers who are farthest away from the transformer receive noticeably less voltage than those who are close to it.

- **Unbalanced phases:** The load cannot be distributed uniformly across all stages due to the random distribution of the load locations. Power losses are caused by the current flowing in the neutral during this unbalanced phase.

- **Poor quality of equipment's:** Low-quality equipment causes significant losses because it draws a lot of electricity and does not fulfill electrical regulations. High current caused I2R losses and heat.

- **Low Power factor:** The ratio of apparent power to actual power is known as the power factor. The system with the lower power factor will have a higher reactive power current, which will result in a higher voltage drop and higher loss when two power factor systems generate the same amount of real power.

Distribution System Techniques for Minimizing Power Loss and Voltage Drop

A distribution feeder's power loss and voltage fluctuations can be reduced using a variety of techniques. Reactive power compensation, conductor grading (network re-conducting), network reconfiguration, sizing and placing distribution transformers optimally, using highly efficient transformers, putting high voltage distribution systems into place, integrating distributed generation, and building new substations are some of these strategies.

The following section covers the approaches used to minimize voltage drop and power loss.(singh, 2018)

Network reconfiguration: It entails adjusting switches to change the circuit architecture while staying within predetermined bounds to cut costs. A number of restrictions are taken into account, including upper and lower bounds for line current and bus voltage. One method for reducing losses in a distribution system is network reconfiguration. By adding more feeder links to form a tree structure or by opening or closing crucial feeder switches, this method modifies the power flow.(Ayodeji Olalekan salau,Yalew Werkie Gebru and Dessalegn Bitew, 2020)

In order to achieve the lowest loss, power distribution networks can be reconfigured to transfer loads from feeders with heavy loads to feeders with lighter loads and from routes with higher resistance to those with lower resistance. The resistance route is the total resistance from the source to the load point. These transfers are successful in improving the voltage profile along the feeder and lowering overall system power losses in addition to modifying the loads on the switched feeder and lowering losses.(Chidanandappa. R, Dr.T.Ananthapadmanabha & Ranjith. H.C, 2015)

Conductor grading: By replacing the current conductor with a new one that is the right size for the intended feeder length while taking cost efficiency into account, conductor grading is a technique used to reduce resistance in a feeder. This can be accomplished by either replacing smaller conductors with larger ones that have a larger cross-sectional area, which lowers the associated resistance, or by installing auxiliary conductors to run in parallel with the current ones. However, the energy savings are frequently outweighed by the expense of the conductors and their installation. Because of this, these methods are rarely used unless there is a particular need, even though they have the potential to significantly reduce losses. When a conductor's performance is jeopardized by rapidly increasing loads, conductor grading is usually used. This method's conductor selection attempts to reduce power loss and voltage drop in the distribution system, which makes it appropriate for emerging countries with substantial yearly population growth (and energy consumption).(Taye, 2019)

Locating and Sizing Distribution Transformers: Even if the secondary voltage level at the distribution transformer is still enough, clients farther away will receive much less power if the transformers are not placed strategically near the consumers. As a result, the distribution system suffers from increased losses. Distribution transformers must be positioned as close to the load center as feasible in order to maintain an ideal voltage level. Additionally, smaller transformers that can efficiently service fewer consumers should be used in favor of bigger ones.

Using a High-Voltage Distribution System: High-voltage cables were moved as close to the load as possible, a variety of small-rated transformers were used in place of large ones, and existing low-voltage distribution systems could be upgraded to high-voltage distribution systems in order to reduce voltage fluctuation and distribution system loss. This approach is more reliable and efficient in distribution networks for reducing technical losses and improving power quality. because the currents in high-voltage devices are comparatively low. However, given the size of the initial investment, it would not be practical.

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Reactive Power Compensation: The method of regulating reactive power to raise the ac power system's efficiency is known as reactive power compensation. Reactive power adjustment issues are often associated with load and voltage support.Reducing current harmonic components caused by large and unpredictable nonlinear industrial loads, improving system power factor, balancing real power drawn from the ac supply, and increasing voltage regulation are the goals of load support. Usually, voltage support is needed at a transmission line termination to reduce voltage swings. By increasing the maximum active power that may be provided, reactive power adjustment in transmission systems increases the stability of the ac system.(Dixon, Juan W and Morán, Luis A, 2008)

Reactive power compensation is generally a significant method of improving a distribution network's voltage profile and loss if the device is correctly sized and located.

2.4 Overview of FACTS

2.4.1 Introduction

"Power-electronic and other static controllers are used to improve controllability and boost power transfer capacity in alternating current transmission systems," according to the IEEE.Solid-state transmission technology was developed in response to the requirement for electrical systems that are more sensitive and efficient. These so-called FACTS devices increase line loads and improve stability, which brings lines closer to thermal limitations.

2.4.2 Classification of FACTS Devices

Several ac transmission system parameters can be controlled by stationary equipment and a power electronic-based system. The research indicates that there are four different kinds of controllers:

1) Shunt Connected FACTS Controllers

To minimize losses and preserve the voltage profile, these FACTS devices strategically place FACTS throughout the network of the power system. The use of shunt controllers to inject current into the line. To provide reactive power, the injected current needs to be in the quadrature phase with the line voltage; otherwise, real power is used. This category includes two varieties of shunt controllers: Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM).

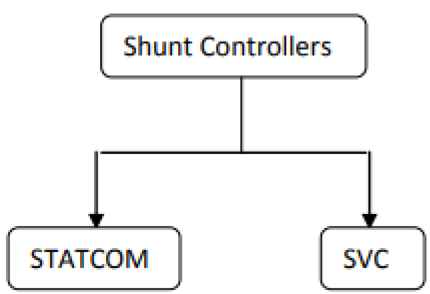

Figure 2.1 Type of shunt controllers (N.Verma, 2014)

I) Static Synchronous Compensator (STATCOM)

According to the IEEE definition, a static synchronous generator that is employed as a shunt-connected static VAR controller enables the output current—whether capacitive or inductive—to be controlled independently of the ac system voltage.Based on a voltage source converter in power electronics, STATCOM is a control system for alternating current electrical transmission networks. Reactive AC can be sent to an electrical device network.STATCOM is a device in the FACTS family. Electrical networks with inadequate voltage regulation and power factor are supported by STATCOM. The application that is utilized the most is voltage stability. STATCOM provides superior damping compared to SVC in terms of a power system's dynamic stability because it can instantly exchange active power with the system.

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II) Static Var Compensator (SVC)

SVC: Static VAR generators or absorbers with shunt connections are defined by the IEEE as devices whose output is modified to switch between capacitive and inductive current in order to control or preserve specific electrical power system parameters. Using TCR and FC/TSC power electronics equipment, SVCs are first-generation FACTS devices that efficiently provide and absorb reactive power to and from the system. The partial conduction control of the thyristor valve modifies the reactance of the TCR, a shunt-connected, thyristor-controlled inductor. By changing the firing angle, the system's reactive power can be changed. There are no harmonics produced by this "continuous control" process.
TSC's "stepwise action by full or zero conduction control" and its capacity to offer low losses, harmonics, redundancy, and flexibility are its most well-known features. It is used to turn on and off shunt capacitor units and is made up of many shunt-connected inductors that a thyristor changes in and out of without altering the firing angle.

2) Series Connected FACTS Controllers

The thoughtful positioning of FACTS devices throughout the power system network is one effective way to regulate power flow and reduce system losses. Series controllers are used to add electricity in series with the transmission line.Reactive power or active power is provided by the injected voltage, depending on whether it is in phase quadrature.

Especially helpful for long-distance transmission lines are these series controllers. The transmission line's reactance can be somewhat reduced by connecting a bank of capacitors in series with the line. Within this device family, series controllers include the thyristor-controlled series capacitor (TCSC), thyristor-switched series capacitor (TSSC), and static synchronous series compensator (SSSC).

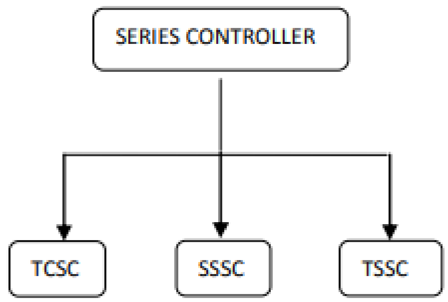

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Figure 2.2 Types of series controller (N.Verma, 2014)

I) TCSC: The IEEE defines a capacitive reactance controller as a reactor operated by a thyristor that switches a bank of series capacitors. The series capacitive reactance can be continuously adjusted thanks to this configuration. The first iteration of FACTS, called Thyristor-controlled series capacitor (TCSC), modifies the line impedance by connected in series with the transmission line is a thyristor-controlled capacitor. Power flow on the AC transmission line can be continuously controlled over a broad range thanks to the TCSC, which operates as a series-controlled capacitive reactance. One can examine the behavior of a changeable inductor coupled in series with a fixed capacitor to comprehend how TCSC works.

II) SSSC: According to the IEEE, a static synchronous generator is used as a series regulator to control the transmitted electric power and adjust the reactive voltage drop across a transmission line. It provides independent controllability by operating without an external power supply and generating a voltage orthogonal to the line current. A transformer and a voltage source are used to link the SSSG in series with the transmission line. For SSSC, a source converter (VSC) is utilized.

An energy source is needed to guarantee a steady voltage supply and make up for VSC losses. Active and reactive power can be exchanged through the use of SSSC. A modest energy supply might be adequate if reactive power balancing is the goal. However, a bigger energy source is required if accurate phase and magnitude adjustment of the injected voltage is desired.
Since the voltage vector and line current form a 90° angle, the voltage can be regulated by accounting for reactive power. At any value and through out any VSC operating time, SSSC can be continually controlled.

TSSC: According to the IEEE, a thyristor-switched reactor provides progressive control of the series capacitance reactance by switching the bank of series capacitors inside a capacitive reactance controller.(N.Verma, 2014)

3) Combined Series-Shunt Controllers

These controllers include elements of series and shunt controllers. Since they may be used to control power flow and voltage profiles, they have the qualities of both kinds of controllers. This reduces losses and enhances system security, flexibility, and dependability. Series-shunt controllers include Unified Power Flow Control (UPFC).
UPFC: The series-shunt controller, like UPFC, combines the features of both controller types like SSSC and STATCOM without the need for an external energy source. These multitasking controllers enable the simultaneous or independent control of variables like bus voltage, phase angle between two buses and the reactance of the transmission line. A highly versatile and sophisticated power electronic device for controlling and optimizing power flow in systems that transmit electrical power, UPFC is specifically made to manage in-phase voltage, quadrature voltage, and shunt compensation. It offers a number of possible benefits for transmission line operations, both static and dynamic. UPFC offers the multifunctional flexibility required to handle a variety of power sector difficulties through real-time control and dynamic compensation.
UPFC successfully controls important factors that affect power flow in transmission lines. increases the flow of both reactive and real power, which, when combined with FACTS devices, helps to improve power system stability.

4) Combined Series-Series Controllers

A coordinated mixture of multiple series controllers is used in multi-lane transmission lines to provide separate reactive compensation in series for each line. It can, however, to transfer actual power between lines, utilize a power connection. Connecting the converters' DC terminals with unified controllers is another method. As a consequence, the transmission line will receive real power. Examples of this kind of application include the Interlink Power Flow Controller (IPFC).(Singh Naveen, AgnihotriPiyush, 2018)

2.4.3 Advantage of FACTS Devices in Distribution Systems

By improving the voltage profile and reducing power loss, they help the system operate at its peak efficiency. Because FACTS controllers are rapid to control, lines' power carrying capacity can be increased up to their thermal limit. By increasing the transient stability limit, the dynamic security of the system is improved. The dynamic overvoltage problem can be resolved with the FACTS controller. Most applications use the controllability to avoid costly or physically taxing extensions of power systems, including upgrades or additions to power lines and substations. FACTS-devices increase the utilization of already-existing installations and provide a more robust reaction to evolving operating circumstances

2.5 Distribution static synchronous compensator

An AC voltage source converter called STATCOM efficiently controls the system's active and reactive power needs by transforming a DC input voltage into an AC output voltage.

STATCOM has clear advantages over SVC (Static Var Compensator). Interestingly, the voltage magnitude no longer influences the highest output of reactive power when the system's voltage falls to a point where the output of STATCOM achieves its maximum capacity. Additionally, STATCOM On a distribution level displays features of steady current when the voltage falls below the specified limit. At the distribution level, these STATCOM devices are commonly referred to as D-STATCOMs (Distribution STATCOMs).(Fahad Iqubal, Mohd Tauseef Khan, Anwar Shahzad Siddiquii, 2017)

Under the FACTS (Flexible AC Transmission System) device category, D-STATCOM, or the Distribution Static Synchronous Compensator, regulates power flow and improve transient stability by the use of force-commutated power electronics in electrical power networks (e.g., GTO or IGBT) as a shunt component. A three-phase Voltage Source Converter (VSC) called the D-STATCOM is connected in parallel with the distribution network to regulate reactive power, enhance power factor, and regulate bus voltage. Both active and reactive current can be injected or absorbed by this device in the common coupling point (PCC). However, because of energy storage limits, the D-STATCOM cannot inject active power for prolonged periods of time. In order to achieve steady-state functioning, reactive power is the main means of power exchange between the D-STATCOM and the system. For steady-state operation, a common D-STATCOM setup includes a DC capacitor, GTO/IGBT, a coupling transformer that exhibits leaky reactance, and a voltage source converter (VSC).(F. Iqbal, M. T. Khan, and A. S. Siddiqui, 2018)
The Figure 2.3 below shows a basic construction of D-STATCOM to the 3-phase distribution line.

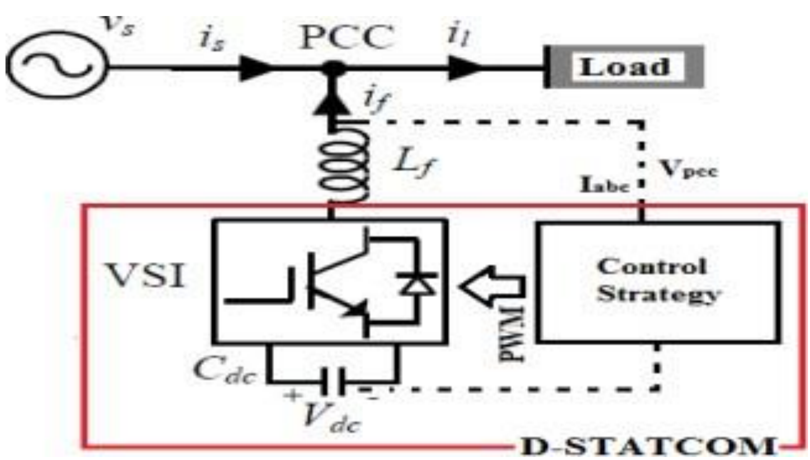

Figure 2.3 Basic Structure of D-STATCOM (Divya B V School of EEE REVA University).

2.5.1 Basic Operating Principle of D-STATCOM

A controller, a coupling transformer, an energy storage device, and a VSC make up a D-STATCOM, a solid-state power electronic switching device. Reactive power can be generated and absorbed by D-STATCOM to provide the necessary compensation. At a PCC with a voltage-quality issue, they are linked to the electricity networks via the D-STATCOM. The controller determines the necessary voltages and currents and compares them to the commands. After generating a sequence of switching pulses to power the converter, the controller uses feedback control.

The output voltage amplitudes are modified in order to exchange reactive power with the network. Phase changes are applied to the system voltage Vs and the Vsc's output voltage. The following describes how the output voltage and the AC system voltage exchange reactive power.

- If Vvsc exceeds Vs, Reactive power will be supplied by the D-STATCOM in capacitive mode, acting as a capacitor.
- If Vs exceeds Vvsc, The D-STATCOM will use reactive power (inductive mode) and function as an inductor.
- If Vvsc = Vs and Reactive power is zero in D-STATCOM's no-load mode, meaning it neither generates nor consumes reactive power.

The three operating modes of D-STATCOMS are shown in Figure 3.4 below:

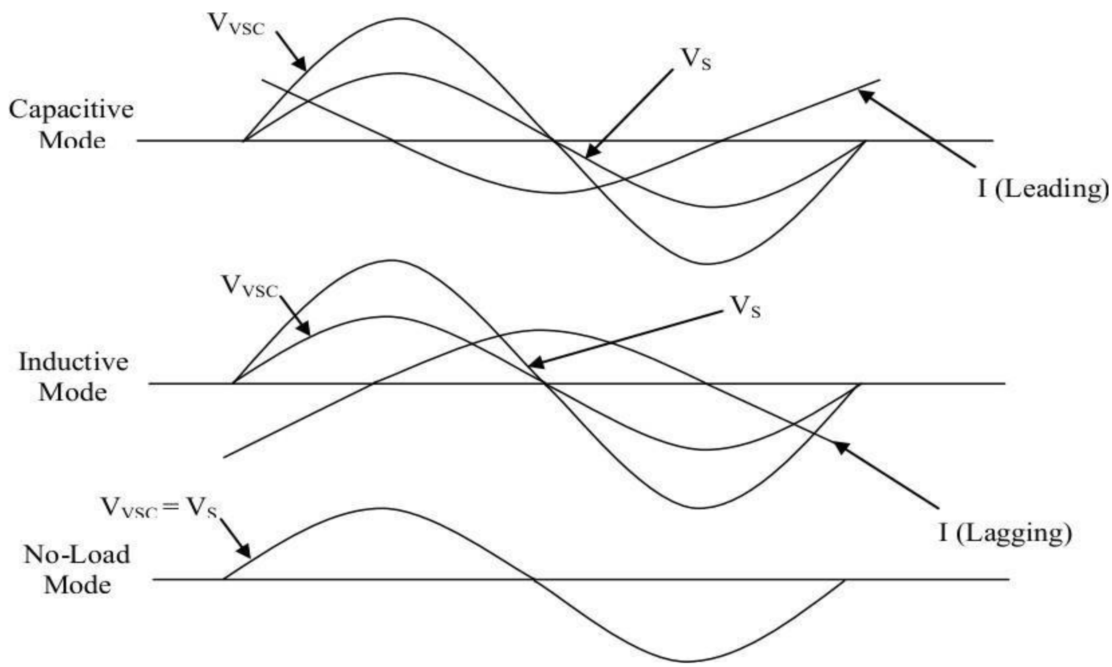

Figure 2.4Operating Modes of D-STATCOM (Asare, 1994)

2.5.2 Components of D-STATCOM

Among the several parts of D-STATCOM is a three-phase inverter that often uses PWM (Pulse Width Modulation) technology with IGBTs (Insulated-Gate Bipolar Transistors), MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors), or SCRs (Silicon-Controlled Rectifiers). Powering the inverter is a DC capacitor that provides a steady DC voltage. High-frequency components caused by the PWM inverter are eliminated by a link reactor that connects the inverter output to the AC supply side filter components. The DC voltage from the capacitor is converted by the inverter into a three-phase voltage that is in sync with the AC source. To ensure proper integration, the link inductor connects the AC supply side to the system voltage.

2.5.3 Reasons for choosing D-STATCOM

Ensuring that the power demand is met while maintaining voltage levels within an acceptable range is a crucial requirement in distribution systems. Two popular techniques for controlling voltage are shunt capacitors and series voltage regulators. However, both of these methods have some drawbacks, Traditional series voltage regulators lack the ability to generate reactive power and have slow response times due to their step-by-step operations However, when shunt capacitors are employed in circuits containing inductive components, they may create oscillations and are unable to provide continuously varying reactive power. Conversely, the shunt FACTS (Flexible AC Transmission Systems) device D-STATCOM is the recommended compensatory device.It provides continuous and variable output without sudden steps, harmonics, or transients, independent voltage regulation, and quicker power factor correction. D-STATCOM can react very instantly, operate close to system stability limitations, and generate and take in reactive power. The reaction starts around 10 ms after the event, achieves full power in 20 to 50 ms, and stays in "hot standby" the entire time, losing roughly 1% of its power. By installing D-STATCOMs, the annual cost savings, power losses, load capacity, stability, and quality of the electricity are all improved.(Wasiak, Irena, RozmyslawMienski, RyszardPawelek, and Piotr Gburczyk, 2007)

2.6 Particle swarm optimization

The best heuristic optimization method for systems made up of multiple-iteration, nonlinear programming problems has been found to be PSO. PSO is regarded as a promising method for attaining better results in terms of the positioning and dimensions of Flexible AC Transmission Systems (FACTS) devices since it can adjust to the responses of the multi-iteration nonlinear power flow algorithm. PSO, a population-based optimization method created especially for continuous nonlinear functions and first presented by James Kennedy and Russell Eberhart in 1995, is a useful tool in this context.(Sanyal, 2021)

PSO begins with a collection of randomly dispersed particles in a search space that represent possible solutions. Because each particle has a unique fitness value, it can be used to solve the problem at hand. The objective is to increase each particle's fitness over time. In each iteration, the velocity of each particle is modified to determine how it moves across the search space. Particles eventually approach optimal solutions through interactions with the group's best solutions and their own best positions. The velocity update considers the best location of the entire swarm, the particle's best position, and its previous velocity. When it comes to addressing optimization problems, PSO is notably good at handling non-linear, non-convex problems with continuous or discrete variables.(Mandefro, 2020)

Advantage and Disadvantages of PSO Technique

Advantages of PSO algorithm

- application to engineering applications as well as scientific research.
- There are no overlapping or mutation calculations in PSO..
- Particle transmission occurs at a very high speed.
- The solution provides a direct description of the real number code that PSO uses..
- has algorithm is derivative-free and has global search efficiency.
- PSO calculations are relatively easy.
- By using the particle's speed, the PSO search can be conducted.

Disadvantages of PSO algorithm

- Partial optimization is a problem with the PSO approach.
- The PSO algorithm's partial optimism makes it harder to control its direction and speed.
- Non-coordinate systems are another issue that the PSO approach is unable to resolve.
- The scattering issue cannot be resolved by the PSO approach.(Andrew Jones,2023)

2.7 Literature Review

To address the issue of power loss and voltage drop in distribution networks, a number of academics have proposed several strategies.

(T. Yuvaraj, K. R. Devabalaji, and K. Ravi, 2015) concentrated on applying the harmony search technique to ascertain the ideal D-STATCOM size and position. Minimizing power loss was considered a single optimization objective function. The suggested approach, which used the BIBC matrix for load flow analysis, was assessed using the IEEE 33-bus system. The distribution system's yearly total loss before and after D-STATCOM was installed was compared in the study. The results indicated a significant reduction in both real and reactive power losses, with a percentage reduction of 28.97% and 28.67% respectively. However, a challenge with this system is the requirement for a large inverter to store the highly variable solar energy and its maintenance. This issue could potentially be addressed by the government by constructing solar grids in parallel to the existing grids.

An technique based on GA-IPSO (Genetic Algorithm and Improved Particle Swarm Optimization) was presented in the work by Charles (2013). To find the best placement and dimensions for multi-type Distributed Generation (DG) units within the IEEE 57-bus test system, the method used a combined sensitivity factor analogy. The main objectives were to decrease power loss and improve the voltage profile of the system.. Up to a certain ideal number of DG units, the author showed that adding DGs to the network reduced volatility drop and system power loss. But further inclusion of DG units beyond this optimal number resulted in a voltage deviation and system loss rise that exceeds allowable bounds. It should be noted that the study did not consider the impact of DG on protection coordination, the specific type of DG technology, or feasibility issues.

Reconfiguring feeders and adding new distribution transformers were suggested as ways to reduce voltage drop and distribution loss in the study by Satrio (2018). This method did not account for the cost implications of adding tie switches and transformers, even though it showed some reduction in loss and voltage drop. The total strategy might not be cost-effective because the cost of these extra parts could lead to a very long payback period.

In their 2019 study, P. Kumarasundari and Dr. Sujatha Balaraman address how the distribution Static Synchronous Compensator (D-STATCOM) and Distributed Generation (DG) can be strategically placed inside distribution networks to enhance the voltage profile and minimize power loss. Since traditional load flow models like Gauss-Seidel, Newton-Raphson, and Fast-Decoupled methods are inappropriate for distribution systems because of their high R/X ratios, the authors suggest minimizing losses by strategically placing DG and D-STATCOM at weak buses within the distribution network. Instead, they use a Direct Load Flow (DLF) analysis that was created especially for distribution systems. They use a 12.6 kV, 100 MVA base MVA IEEE 69 bus radial distribution system as the test system for their investigation. The Loss Sensitivity Factor (LSF), which suggests the best places is used to determine the best location for DG and D-STATCOM in the distribution network. The authors draw the conclusion that putting D-STATCOM and DG on the same bus enhances the voltage profile of the network overall and lowers the total real and reactive power losses.The size of the D-STATCOM and DG is determined by the number of buses that violate limits, and the injected reactive power should not exceed the reactive power demand of the respective bus.

(Amin, Amal, Salah Kamel, Ali Selim, and LoaiNasrat., 2019) present a hybrid analytical-coyote optimization technique (COA) to find the best location and size of Distribution Static Synchronous Compensators (D-STATCOMs) with the aim of improving voltage profiles and minimizing active power losses while taking operational constraints into account. The analytical technique is used to find the right D-STATCOM sizes, and the COA is used to find suitable locations within the Radial Distribution System (RDS).
However, despite the power loss minimization achieved through this approach, the results do not meet the acceptable range specified by IEEE standards.

CHAPTER THREE

3. Materials and Methods

3.1 Introduction

In the power system, the electrical power distribution system is the biggest part. It is made up of distribution feeders, distribution transformers, loads, and connected equipment. Distribution transformers employ the power that passes through distribution feeders to supply clients with the power they require. To complete their everyday responsibilities, the clients require an adequate level of power. However, the largest obstacle to distributed power delivery to clients is the loss of power and voltage during transit.

Identifying the issue in order to address the public concern was the first stage in this thesis. In order to find answers to our problems, the writings of other authors were then gathered, including books, journals, essays, and papers on related topics.

Distribution substation power loss and voltage drop were the issues mentioned in the problem statement. A comprehensive literature research was conducted in order to better understand how to improve the voltage profile and decrease this power loss in distribution networks. Information was gathered and examined for the case study. The acquired data was arranged so that it could be applied to decrease distribution power loss and improve voltage profiles. Next, load flow analysis was performed on the Adametulu distribution substation network for Bote town Meki-Alemtena feeder under base case operating conditions and following the installation of D-STATCOM in the weak bus. This was done using MATLAB software to identify the weak bus using the bus voltage stability index and particle swarm optimization algorithm. Finding out how well D-STATCOM works to reduce power loss and enhance the bus voltage profile of the Bote town Meki-Alemtena feeder at the Adametulu distribution substation is the goal of this analysis. Starting with problem identification, the job is carried out by simulating the network with the best D-STATCOM placement and size.

3.2 Data collection

Primary and secondary data collecting are the two categories of data collection techniques. Most of the data was collected at the Adametulu substation and the Ethiopian Electric Utility (EEU) Adama Region. These data were gathered by observation and interview. Secondary data was collected from published publications, journals, manufacturer data tables, published reports, and other sources. Conductor impedance, feeder bus and line data, historical substation feeder loading (peak load) data, and other pertinent data were used to create the information. A clap meter was used to measure the voltage on the secondary side of some of the newest transformers in order to determine whether the chosen distribution feeder had any voltage drops.

One of the current substations in the EEP power system network is the Adametulu distribution substation, which is situated in the Adama region of the nation. One 132kV transmission line supplies power to this substation from the Adametulu substatin. In addition to a substation with a 132/33 KV, 50 MVA transformer, there are two transformers within the substation with capacities of 132/33/15 KV and 25 and 31 MVA apiece. Two outgoing feeders (Korme and Meki-Alemtena) are located on the 33kV side of the substation, and five outgoing feeders (Zeway, Meki, Bulibula, Cosatic, and Industry) are located on the 15kV side.

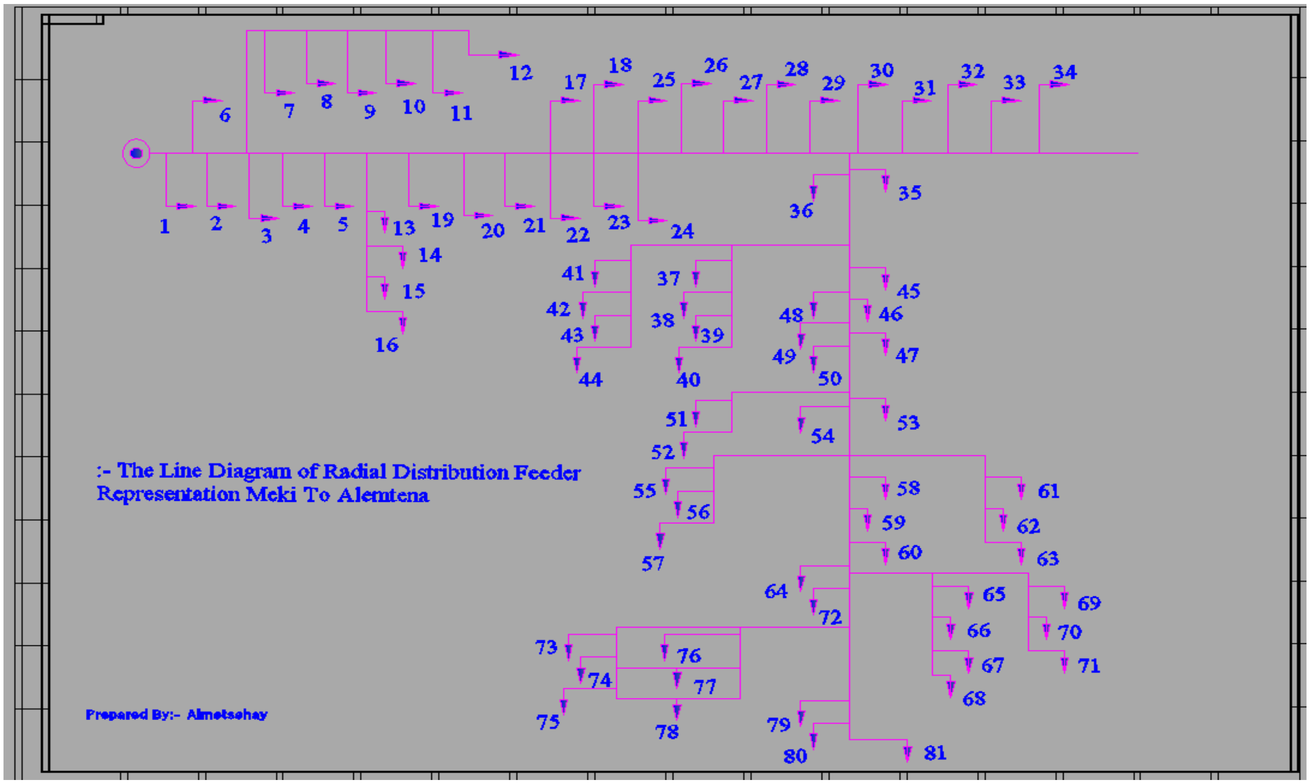

Figure 3.1 The illustration of the radial distribution feeder line diagram Meki-Alemtena

Figure 3.1, which is seen above, shows the Meki-Alemtena feeder's single line diagram. There are 81 bus feeders in all, and the feeder is arranged radially. Node 1 serves as a reference node or slack bus, while the other 80 nodes are used to link to loads through step-down distribution transformers. The feeder's total length is 71.9249 kilometers, and it uses AAC-50 and AAC-95 stranded conductors. The medium voltage (33 kV) power is transmitted from the Adametulu substation to the distribution transformers via these overhead lines.

3.2.1 Line data

From the collected data, the lengths of each main and branch feeder have been measured, as shown in Table 1. For the various lines of the Meki-Alemtena outgoing distribution feeder Adametulu substation, a variety of conductor types are installed.

Table 3.1 Route length specifications for the 33KV outgoing feeder of the Adametulu substation Meki-Alemtena collection from EEU

From Bus	To Bus	Length (km)		From Bus	To Bus	Length (km)
1	2	0.493		41	42	1.35
2	3	0.469		42	43	1.72
3	4	0.03		43	44	2.44
4	5	0.184		37	45	6.46
1	6	0.107		45	46	2.39
2	7	0.4		37	47	3.9
7	8	0.01		47	48	1.25
8	9	0.223		48	49	1.14
9	10	0.152		49	50	0.826
10	11	0.181		50	51	0.051
11	12	0.131		51	52	1.17
5	13	0.289		52	53	0.149
5	14	0.338		53	54	0.25
14	15	0.658		54	55	0.675
15	16	0.428		55	56	0.113
13	17	0.305		55	57	0.139
17	18	0.295		57	58	0.338
18	19	0.418		58	59	0.369
18	20	1.03		59	60	0.398
20	21	0.46		60	61	0.0075
21	22	0.792		61	62	0.411
22	23	1		62	63	0.0075
23	24	0.475		59	64	0.387
24	25	0.259		64	65	0.067
25	26	0.18		65	66	0.643
26	27	0.06		66	67	0.0034
27	28	0.335		59	68	0.555
28	29	3.82		68	69	0.213
29	30	0.686		69	70	0.233
30	31	2.73		69	71	0.031
31	32	0.203		59	72	3.12
32	33	1.1		71	73	0.748
33	34	1.68		73	74	0.332
34	35	0.589		74	75	0.253
35	36	0.017		75	76	0.633
36	37	3.4		76	77	3.4
37	38	1.8		77	78	0.737
38	39	0.485		78	79	1.29
39	40	1.76		79	80	0.084
40	41	1.51		80	81	4.82

The material, size, configuration, length, spacing, and distance between conductors all affect their impedance, which is used in the power distribution system. Adametulu distribution feeders use stranded conductors with a frequency of 50 Hz and a length of one kilometer.They are also used to measure the inductive reactance. The following equations are then used to compute the impedances, and Table 3.4 displays the results..(P. Delivery and S. Member,, 1999)(P. Grid, 2015)

The feeder's impedance measured in ohm can be obtained using the following equation

$$Za = Ra + j0.06283 \ln\left(\frac{D}{GMRa}\right)\Omega / km \quad 3.1$$

$$D = \sqrt[3]{DabBbcCac} \quad 3.2$$

$$GMR = k \times r \quad 3.3$$

Where: -

Za = Impedance of conductor in Ω/ *km*

Ra = Resistance of conductor in Ω/ *km*

Dab, *Dbc*, *Dac*, = Distance between conductors a and b, b and c, a and c in meter

GMRa = Geometric mean radius of conductor a

k = GMR factor

r = Actual conductor radius

Table3.2 The specifications of the overhead conductor

Conductor Type	Conductor size (mm2)	Actual area (mm2)	Stranding and wire diameter	Overall diameter of conductor (mm)	Actual diameter (mm)	GMR (mm)	Resistance (Ω/km)
AAC	50	49.5	7/3.0	9	7.9377	2.88	0.5785
AAC	95	93.5	19/2.5	12.5	10.897	4.129	0.3085

Table3.3 Strand Relationship and GMR Factor (k) for AAC conductor

Strands	GMR factor, k
7	0.7256
19	0.7577
37	0.7678
61	0.7722

The following conductors are used for Meki-Alemtena outgoing feeder, which is obtained from Adametulu Substation SCADA drawing.

Overhead lines used for feeder Meki-Alemtena

- AAC 95 sq. mm and AAC 50 sq. mm

Using equation 3.1, Table 3.2 and Table 3.3 the following results are obtained.

A. For AAC-50 conductor type, the positive sequence impedance is $Z_{50} = 0.5785 + j0.3470$ Ω/km

B. For AAC-95 conductor type, the positive sequence impedance is $Z_{95} = 0.3085 + j0.3244$ Ω/km

The impedance per kilometer times the length of the line segment, as shown in Table 3.4, yields the positive sequence impedances for the line segments. Due to the short length of the line, overhead line shunt admittance is disregarded.

Table 3.4 Meki-Alemtena-line data for the 33KV feeder at the Adametulu substation

From Bus	To Bus	Conductor Type	R (ohm	X(ohm)
1	2	AAC95	0.1520905	0.1599292
2	3	AAC95	0.1446865	0.1521436
3	4	AAC50	0.0017355	0.001041
4	5	AAC95	0.056764	0.0596896
1	6	AAC95	0.0330095	0.0347108
2	7	AAC50	0.2314	0.1388
7	8	AAC50	0.0005785	0.000347
8	9	AAC95	0.0687955	0.0723412
9	10	AAC95	0.046892	0.0493088
10	11	AAC95	0.0558385	0.0587164
11	12	AAC95	0.0404135	0.0424964
5	13	AAC95	0.0891565	0.0937516
5	14	AAC95	0.104273	0.1096472
14	15	AAC50	0.380653	0.228326
15	16	AAC50	0.247598	0.148516
13	17	AAC50	0.1764425	0.105835
17	18	AAC50	0.1706575	0.102365
18	19	AAC50	0.241813	0.145046
18	20	AAC50	0.595855	0.35741
20	21	AAC95	0.14191	0.149224
21	22	AAC95	0.244332	0.2569248
22	23	AAC95	0.3085	0.3244
23	24	AAC95	0.1465375	0.15409
24	25	AAC95	0.0799015	0.0840196
25	26	AAC95	0.05553	0.058392
26	27	AAC95	0.01851	0.019464

27	28	AAC50	0.1937975	0.11645
28	29	AAC50	2.20987	1.32554
29	30	AAC50	0.396851	0.238042
30	31	AAC95	0.731145	0.768828
31	32	AAC95	0.0626255	0.0658532
32	33	AAC95	1.2991	0.41096
33	34	AAC50	1.98408	0.627648
34	35	AAC50	0.695609	0.2200504
35	36	AAC50	0.0098345	0.005899
36	37	AAC50	1.9669	1.1798
37	38	AAC50	1.0413	0.6246
38	39	AAC50	0.2805725	0.168295
39	40	AAC50	2.07856	0.657536
40	41	AAC50	0.873535	0.52397
41	42	AAC50	0.780975	0.46845
42	43	AAC50	0.99502	0.59684
43	44	AAC50	1.41154	0.84668
37	45	AAC50	3.84124	2.24162
45	46	AAC50	2.82259	0.892904
37	47	AAC50	4.6059	1.45704
47	48	AAC50	1.47525	0.467
48	49	AAC50	1.34634	0.425904
49	50	AAC50	0.975506	0.3085936
50	51	AAC50	0.060231	0.0190536
51	52	AAC50	1.38177	0.437112
52	53	AAC50	0.175969	0.556664
53	54	AAC50	0.144625	0.08675
54	55	AAC50	0.3904875	0.234225
55	56	AAC50	0.03653705	0.039211
55	57	AAC95	0.0428815	0.0450916
57	58	AAC95	0.104273	0.1096472
58	59	AAC95	0.1138365	0.117036
59	60	AAC95	0.122783	0.1291112

60	61	AAC95	0.0231375	0.02433
61	62	AAC95	0.1267935	0.1333284
62	63	AAC95	0.0231375	0.0233
59	64	AAC50	0.2238795	0.134289
64	65	AAC50	0.0387595	0.023249
65	66	AAC50	0.3719755	0.223121
66	67	AAC50	0.019669	0.011798
59	68	AAC50	0.3210675	0.192585
68	69	AAC50	0.1232205	0.073911
69	70	AAC50	0.275173	0.0870488
69	71	AAC50	0.036611	0.0115816
59	72	AAC50	1.80492	1.08264
71	73	AAC50	0.432718	0.259556
73	74	AAC50	0.192062	0.115204
74	75	AAC50	0.1463605	0.087791
75	76	AAC50	0.3661905	0.219651
76	77	AAC95	4.0154	1.27024
77	78	AAC95	0.870397	0.2753432
78	79	AAC95	1.52349	0.481944
79	80	AAC95	0.099204	0.0313824
80	81	AAC95	5.69242	1.800752

Table3. Adametulu substation 33KV feeder Meki-Alemtena load data collected from EEU

Bus	load P(MW)	Load Q(MVAr)		Bus	load P(MW)	Load Q(MVAr)
2	0.16	0.12		42	0.04	0.03
3	0.25	0.189		43	0	0
4	0.04	0.03		44	0.08	0.12
5	0.16	0.12		45	0	0
6	0.16	0.12		46	0.16	0.12
7	0.08	0.06		47	0.04	0.03
8	0.16	0.12		48	0.16	0.12
9	0.16	0.12		49	0.25	0.189
10	0.08	0.06		50	0.16	0.12
11	0.16	0.12		51	0.04	0.03
12	0.16	0.12		52	0.04	0.03
13	0.08	0.06		53	0.08	0.06
14	0.02	0.015		54	0.02	0.015
15	0.08	0.06		55	0.08	0.06
16	0.25	0.189		56	0.25	0.189
17	0.02	0.015		57	0.16	0.12
18	0.16	0.12		58	0.16	0.12
19	0.02	0.015		59	0.25	0.189
20	0.08	0.06		60	0.08	0.06
21	0.02	0.015		61	0.08	0.06
22	0.08	0.06		62	0.04	0.03
23	0	0		63	0.04	0.03
24	0.16	0.12		64	0.25	0.189
25	0.25	0.189		65	0.25	0.189
26	0.04	0.03		66	0.04	0.03
27	0.02	0.015		67	0.02	0.015
28	0.16	0.12		68	0.25	0.189
29	0.25	0.189		69	0.25	0.189
30	0	0		70	0.02	0.015
31	0.25	0.189		71	0.16	0.12
32	0	0		72	0.04	0.03
33	0.02	0.015		73	0	0
34	0.16	0.12		74	0.08	0.06
35	0.25	0.189		75	0.504	0.378
36	1.25	0.75		76	0.04	0.03
37	0.08	0.06		77	0.16	0.12
38	0	0		78	0	0
39	0.04	0.03		79	0.02	0.015
40	0.04	0.03		80	0.25	0.189
41	0	0		81	0.16	0.12

3.3 Load Flow Analysis for Radial Distribution System

Establishing the currents at every branch and the voltages at every node is one of the most crucial tasks in power system regulation: load flow analysis. Since the load flow method's results offer valuable insights into the power system, several investigations would not be feasible. Absent them. By employing load flow algorithms, further power system investments in sensor and communication infrastructure are not required. Numerous tools used to monitor, evaluate, and operate the power system also incorporate results of load flow. Among the various power system applications that use load flow analysis directly or indirectly are power systems optimization, network reconfiguration and service restoration, power quality enhancement, distributed generator and capacitor placements, and cost-effective dispatch.Power flow analysis has been established utilizing several load flow approaches in both transmission and distribution networks. Power flow in distribution networks is commonly analyzed using the backward/forward sweep (BFS) and direct load flow (DLF) techniques. In power transmission systems, Gauss-Seidel, Newton Raphson, and fast-decoupled techniques are frequently used. The high resistance (R) to reactance (X) ratio in distribution networks might make the load flow techniques employed in a power transmission network perform poorly. The Newton-Raphson approach still takes a lot of calculation time for distribution network applications, despite some researchers' advancements. Because it is more appropriate for distribution systems, the backward/forward sweep (BFS) power flow analysis using Kirchhoff's rules is employed in this study. (Al, 2021).

3.3.1 Forward / Backward Sweep Load Flow Method

Each bus in the radial distribution network has a distinct route back to the source, which makes it unique.The backward/forward sweep algorithm consists of forwarding and/or backward sweep operations that utilize the radial network structure. Its foundation is the updating of currents and voltages along these discrete paths. The forward sweep starts at the sending end and proceeds to the far end of feeds in order to ascertain the node voltages. Determine the voltage drop that results from the currents or power flows that are injected into each lateral in order to update the end voltages. It is predicated on the boundary condition specified by the source voltage. It primarily entails computing voltage dips while maybe updating for power or current flows.

On the other hand, the branch current or power can be obtained by sweeping the feeder and laterals backward from the far end to the sending end. Its foundation is the boundary condition that no power or current is escaping from the lateral end. Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) are applied to backward and forward propagations, respectively, to create two derived matrices known as the bus-injection to the branch-current matrix (BIBC) and the branch current to the bus-voltage matrix (BCBV), which are used to carry out the load flow.(J. A. Michline Rupa and S. Ganesh, 2014)

a) Bus Injection to Branch Current (BIBC) Matrix (Backward Sweep)

Every iteration k collects the branch currents from loads to origin. The branch current can only be calculated once the current injected at each bus and the bus-injection to branch current (BIBC), which connects the bus injected current to the branch current, have been determined. The current injection at the ith bus's kth iteration is

$$I_i^k = \left(\frac{S_i}{v_i^k}\right) = \left(\frac{P_i + jQ_i}{v_i^k}\right) \qquad 3.4$$

$$S_i = P_i + jQ_i \qquad 3.5$$

Where: -

V_i^k and I_i^k is the bus voltage and equivalent current injection of the i^{th} bus at the k^{th} iteration, respectively.

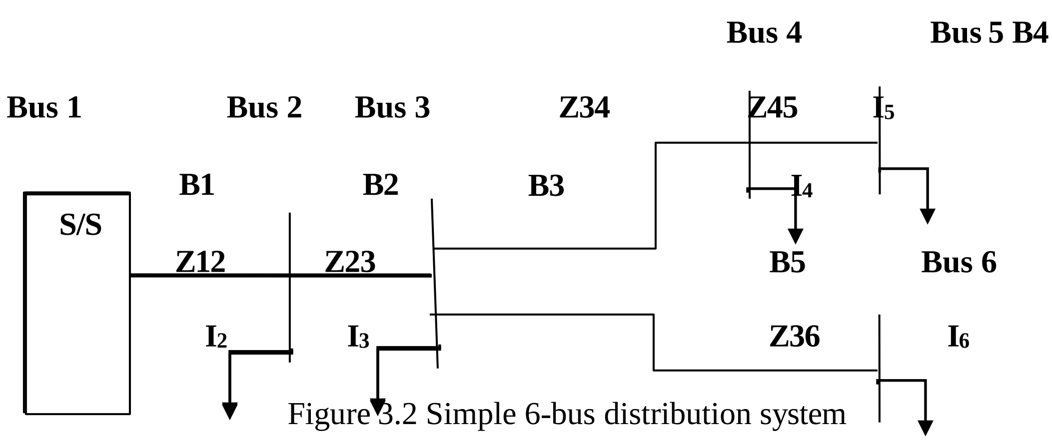

Figure 3.2 Simple 6-bus distribution system

The branches current is now determined using Kirchhoff's current law (KCL) on the sample shown in figure 3.2. When described in terms of injections of equal current (Ii), the branch currents (Bi) can be written as

$B_1 = I_2 + I_3 + I_4 + I_5 + I_6$

$B_2 = I_3 + I_4 + I_5 + I_6$ 3.6

$B_3 = I_4 + I_5$

$B_4 = I_5$

$B_5 = I_6$

Consequently, the following matrix can be used to characterize the relationship between the branch currents and the bus current injections:

$$\begin{bmatrix} B1 \\ B2 \\ B3 \\ B4 \\ B5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I2 \\ I3 \\ I4 \\ I5 \\ I6 \end{bmatrix} \quad 3.7$$

Equation (3.7) can be expressed as

$$[B] = [BIBC][I] \quad 3.8$$

Where: -

For the specified sample network, BIBC stands for bus injection branch current.

b) Branch Current to Bus Voltage (BCBV) Matrix (Forward sweep)

We now apply Kirchhoff Voltage Laws (KVL) using the previously determined branch current vector B and branch-current to bus-voltage (BCBV) values.Branch current and bus voltage can be connected using the following formulas

$$V_2 = V_1 - B_1 Z_{12} \quad 3.9$$

$$V_3 = V_2 - B_2 Z_{23} \quad 3.10$$

$$V_4 = V_3 - B_3 Z_{34} \quad 3.11$$

$$V_5 = V_4 - B_4 Z_{45} \quad 3.12$$

$$V_6 = V_5 - B_5 Z_{36} \quad 3.13$$

Where: -

V_i is the voltage of bus i

Z_{ij} is the impedance of the line between buses I and J.

The substation voltage, line characteristics, and branch currents can all be used to express the bus voltage. You can alter and rearrange the bus voltage calculations above to become

$$V_2 = V_1 - B_1Z_{12} \qquad 3.14$$

$$V_3 = V_1 - B_1Z_{12} - B_2Z_{23} \qquad 3.15$$

$$V_4 = V_1 - B_1Z_{12} - B_2Z_{23} - B_3Z_{34} \qquad 3.16$$

$$V_5 = V_1 - B_1Z_{12} - B_2Z_{23} - B_3Z_{34} - B_4Z_{45} \qquad 3.17$$

$$V_6 = V_1 - B_1Z_{12} - B_2Z_{23} - B_3Z_{34} - B_{4_5}Z_{45} - B_5Z_{36} \qquad 3.18$$

It is possible to modify and rearrange the bus voltage calculations above to get

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \qquad 3.19$$

$$\Delta V] = [BCBV][B] \qquad 3.20$$

In general form, i and k represent the node and iteration number, respectively.

$$I_{i-1,i}^{k} = I_i^k + I_{i,i+1}^{K} \qquad 3.21$$

$$V_i^k = V_{i-1}^k - Z_{i-1}, iI_{i-1,i}^{k-1} \qquad 3.22$$

Power Loss Calculation

The distribution line's power loss can be computed as

$$P_{loss(i,i+1)} = |I_i|^2 R_{i,i+1} = \frac{P_i^2 + Q_i^2}{|V_i^2|} R_{i,i+1} \qquad 3.23$$

$$Q_{loss(i,i+1)} = |I_i|^2 X_{i,i+1} = \frac{P_i^2 + Q_i^2}{|V_i^2|} X_{i,i+1} \quad 3.24$$

$$P_{loss} = \sum_{i=1}^{N} P_{loss(i.i+1)} \qquad 3.25$$

$$Q_{loss} = \sum_{i=1}^{N} Q_{loss(i.i+1)} \quad 3.26$$

Voltage Drop Calculation

Every component of the power system, from the generator to the customer's meter, has voltage dips. The distribution system's voltage drop can be computed as.(B. Singh and M. K. Yadav, 2018)

$$\Delta V = \sqrt{3} \times \sum_{i=1}^{n} (R_i \cos\theta + X_i \sin\theta)\, L_i \quad 3.27$$

Where: -

I_i Portion current on line (A)

θ Angle between current and voltage

R_i Resistance of the line (Ohm/km)

X_i Reactance of the line (Ohm/km)

N Number of portions

L_i Portion length of the line (km)

The flow chart of backward forward sweep load flow method can generally be summarized In short and precise form as follows.

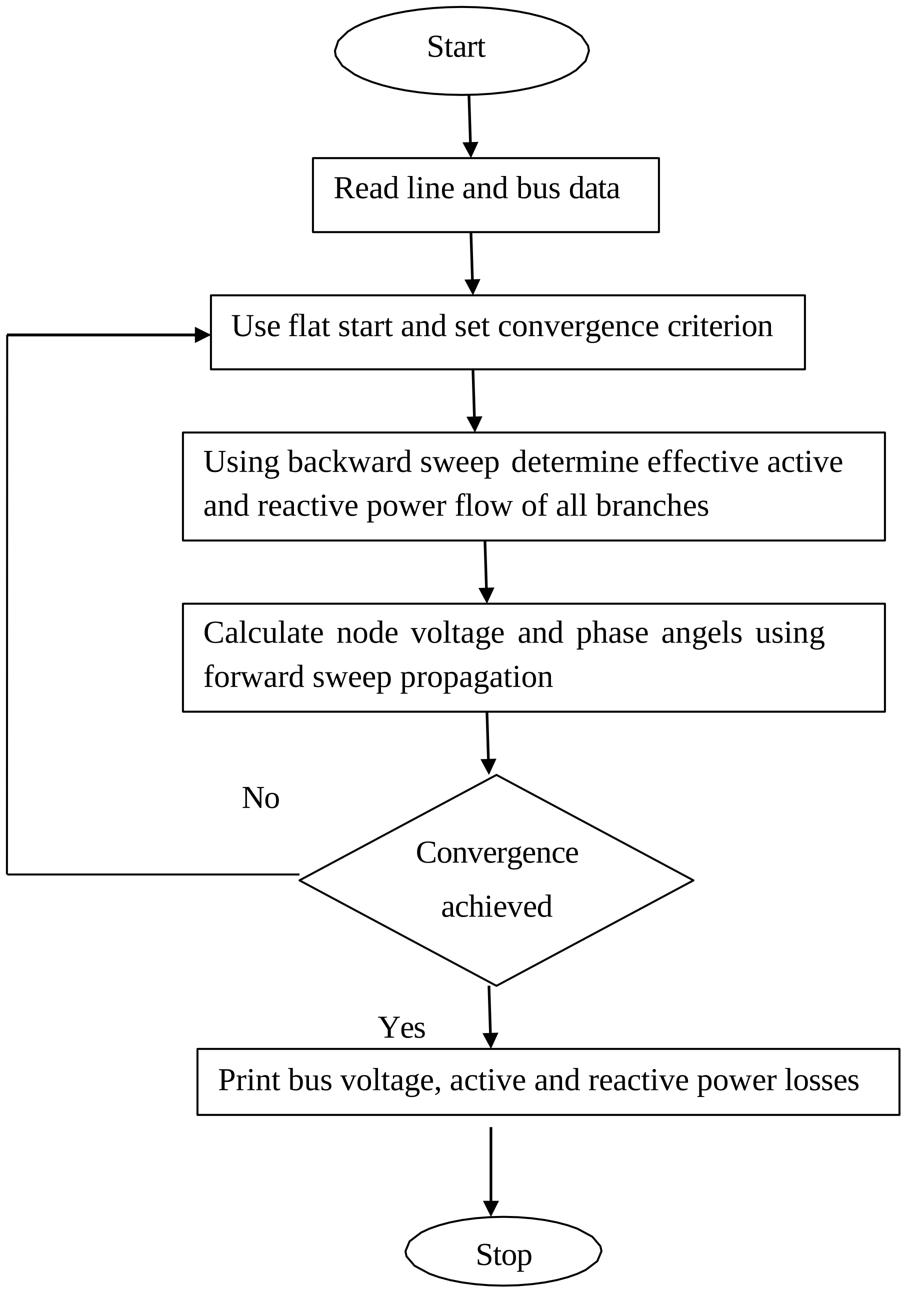

Figure 3.3 Flow chart for forward backward sweep method

3.4 Mathematical Modeling of D-STATCOM

The mathematical modeling of D-STATCOM is shown in this part. Power is delivered from a single side in the great majority of radial distribution systems. This article describes the steady-state mathematical modeling of D-STACOM, using Figure 3.4 to illustrate a basic two-bus radial distribution system.

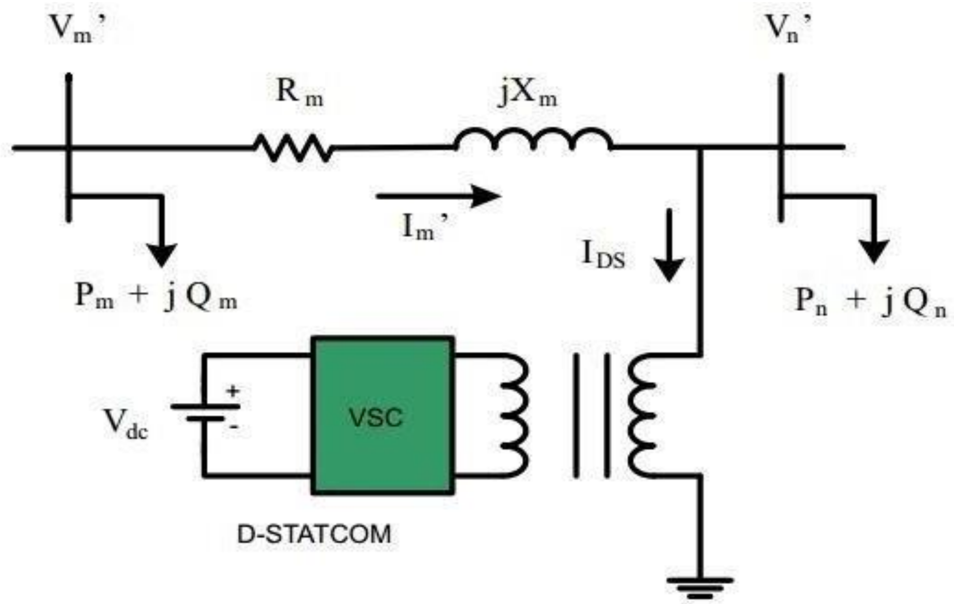

Figure 3.4 Diagram of two busses on a single line with D-STATCOM included.

(Fahad Iqubal, Mohd Tauseef Khan, Anwar Shahzad Siddiquii, 2017)

In most distribution systems, which are usually of the radial kind, electrical power is frequently supplied from one side. Figure 3.4 illustrates the D-STATCOM installation at bus "m+1". In this case, "rm" stands for line resistance and "xm" for line reactance between bus's "m" and "m+1." "Pm + jqm" and "Pm+1 + jqm+1" stand for the local loads connected to buses "m" and "m +1," respectively. In the same way, the voltages at the bus's "m" and "m+1" are denoted by Vm and Vm+1.

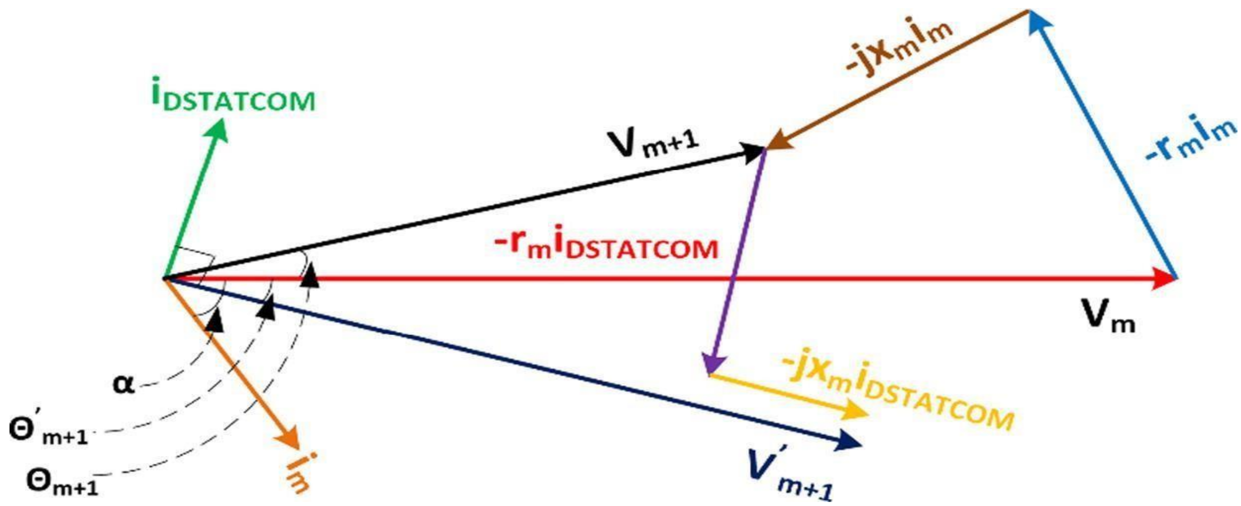

Figure 3.5 Phasor diagram of voltage and current of the system after DSTATCOM consideration (Fahad Iqubal, Mohd Tauseef Khan, Anwar Shahzad Siddiquii, 2017).

Figure 3.5 illustrates the two-bus system's phasor diagram, which is displayed in figure 3.4.For a conventional radial network, the voltage values at the buses are less than 1p.u. In this case, the voltage value at bus "m+1" is assumed to be less than 1p.u. and D-STATCOM is installed in this bus to improve the voltage profile.

Considering Vm as reference bus

- $V'_{m+1} < \theta'_{m+1}$: the voltage value of bus ‗m+1‘ after consideration of D-STATCOM
- $V_m < \theta_m$: the voltage value of bus ‗m‘
- $i_m < \alpha$: the current flow in the line after considering D-STATCOM
- $i_{DSTATCOM} < (\theta_{m+1} + 90^0)$: the current injected by D-STATCOM

The size of D-STATCOM is then calculated numerically using the phasor diagram above as follows:

$$V'_{m+1} < \theta'_{m+1} = V_m < \theta_m - (R_m + jx_m) i_m < \alpha - (R_m + jx_m) i_{D-STATCOM} < (\theta'_{m+1} + \frac{\pi}{2}) \quad 3.28$$

Then equating real and imaginary part of equation 3.28

Real part of the equation is:

$$V'_{m+1}\cos\theta_{m+1} = Re(V_m < \theta_m) - Re(r_m i_m < \alpha) + x_m i_{D-STATCOM} \times \sin(\theta'_{m+1} + \frac{\pi}{2}) - r_m i_{D-STATCOM}\cos(\theta'_{m+1} + \frac{\pi}{2}) \qquad 3.29$$

Imaginary part of the equation is:

$$V'_{m+1}\,\mathrm{Sin}\,\theta_{m+1} = Im(V_m < \theta_m) - Im(x_m i_m < \alpha) - x_m i_{DSTATCOM} \times \mathrm{Cos}(\theta'_{m+1} + \frac{\pi}{2}) - r_m i_{DSTATCOM}\,\mathrm{Sin}(\theta'_{m+1} + \frac{\pi}{2}) \qquad 3.30$$

For For simplicity, let us use the notations

$A=(V_m < \theta_m) - Re(r_m i_m < \alpha)$

$B= (V_m < \theta_m) - (x_m i_m < \alpha)$

$C_1= r_m$

$C_2= x_m$

$D = V'_{m+1}$

$U = i_{DSTATCOM}$

$W = \theta'_{m+1}$

$$D\sin W = B + C_2 U Sin W - C_1 U\,\mathrm{Cos}\,W \qquad 3.34$$

Using this notation equation 3.29 and 3.30 can be written as becomes

$$D\cos W = A + C_2 U\sin(W + \frac{\pi}{2}) - C_1 U\cos(W + \frac{\pi}{2}) \qquad 3.31$$

$$D\sin W = B - C_2 U\,\mathrm{Cos}(W + \frac{\pi}{2}) - C_1 U\,\mathrm{Sin}(W + \frac{\pi}{2}) \qquad 3.32$$

Using trigonometric identity equation 3.31 and 3.32 can be written as becomes

$$D\cos W = A + C_2 U\,\mathrm{Cos}\,W + C_1 U Sin W \qquad 3.33$$

Here A, B, C1 and C2 are constants, D is the magnitude of compensated voltage (1p.u) and the variables are U and W.

$$U = \frac{DcosW - A}{C_2U\, Cos\, W + C_1USin\, W} \quad 3.35$$

$$U = \frac{DsinW - B}{C_2USin\, W - C_1U\, Cos\, W} \quad 3.36$$

Then through taking X=$sinW$ and equating equation 3.29 and 3.30 we get the following most simplified quadratic equation

$$(K_2^1 |+ K_2^2)X^2 - (2K_1DC_1)X + \left(D^2C_1^2 - K_2^2\right) = 0 \quad 3.37$$

Where K1=$AC2-BC1$ and K2=$AC1-BC2$

The solution of Equation 3.37 can be written as become

$$X = \frac{-b \pm \sqrt{\varphi}}{2a} \quad 3.38$$

Where, $\varphi = b^2 - 4ac$

$a = K_2^1 + K_2^2$, $b = 2K_1DC_1$, and $c = D^2C_1^2 - K_2^2$

As proven with the aid of using equation 3.38, Only one of the two values that are determined for the variables W and U is acceptable because there are two roots for X. These roots are analyzed in the load flow results under boundary circumstances in order to identify the right response i.e., if the value of D=Vm+1, then U=I D-STATCOM=0 and the angle before compensation and after compensation become equal. This implies that D-STATCOM is neither generating nor absorbing any reactive power.

Then the root of equation $X = \frac{-b+\sqrt{\varphi}}{2a}$ is selected for correct answer for equation 3.38.

W $= \theta_{m+1} = \sin^{-1} X$ 3.39

The following will then be the injected current, voltage, and reactive power at bus "m+1."

$$V'_{m+1} = V'_{m+1} < \theta'_{m+1} \qquad 3.40$$

$$i_{DSTATCOM} = i_{DSTATCOM} < \left(\theta'_{m+1} + \frac{\pi}{2}\right) \qquad 3.41$$

$$\mathrm{j}q_{\mathrm{D-STATCOM}} = V'_{m+1} \mathrm{i}^{*}_{\mathrm{D-STATCOM}} \qquad 3.42$$

Where, * represents conjugate of complex variable

3.5 Optimal Sizing & Location of D-STATCOM

The overall goals of the thesis were to reduce the amount of power loss, enhance the voltage profile, and stabilize the voltage by employing particle swarm optimization algorithms. Particle swarm optimization and the voltage sensitivity factor are used to find the search space. The initial requirement is to assign the voltage sensitivity factor to potential buses in order to determine the optimal D-STATCOM placement. In the second condition, PSO and the new best method were used to establish the ideal D-STATCOM size. Lastly, from a variety of different objective functions, the power distribution system anticipates that the system will achieve a number of constraints within the multi-objective function. The routines additionally handle the randomly generated switching condition for D-STATCOM sizing. When using D-STATCOM, the voltages of all the busses should be within the permitted deviation range of 0.95 to 1.05 p.u. D-STATCOM's optimal placement is determined by the total system losses as well as the permitted voltage variation range.

3.5.1. Problem Formulation

In an optimization problem, various targets may be considered. Three terms are taken into consideration by the objective function in this study, and all three terms are optimized using the optimizer. The study aims to improve the voltage profile, increase voltage stability, and reduce active and reactive losses. After that, each thought is subjected to the objective function while accounting for the weighting coefficients. System loss, the first term in the objective function, is defined in the subsection that follows.

- **Power loss**

The following formula can be used to determine the distribution system's overall losses:

$$f_1 = \sum_{i=1}^{nb} R_i * i_i^2 \quad 3.43$$

Where: -

f_1: is objective function representing active power loss

: is the line resistance of branch i,

i_i: is the current of line i

nb: is the number of system branches

$$Q_{loss} = \sum_{i=1}^{nb} x_i * i_i^2 \quad 3.44$$

Where: -

Q_{loss}: is the reactive power loss

xi: is the reactance of line i

$i\ 2$: is the current of line i

nb: is the number of system branches

Voltage Profile enhancement

As stated in the previous section, D-STATCOM can enhance the voltage profile and balance reactive power. The objective function for enhancing the voltage profile is expressed as follows.

$$f_2 = \sum_{i=1} (v_{norm} - v_i)^2 \quad 3.45$$

Where: -

f_2 : is the goal function for improving the voltage profile.

v_{norm}: is the system's nominal voltage, which is equivalent to one p.u.

: is the voltage of the i^{th}bus

$n_{bus:}$ is the number of system buses

Voltage stability Improvement

Numerous indices are used to assess the security of the power system. A potential bus or the bus that is the weakest of all the buses can be found in a number of methods. PSO is utilized in this study to identify D-STATCOM's ideal position. To optimize the voltage profile and lower power loss, D-STATCOM will be installed on the candidate bus, which is the bus with the lowest stability index value. In this part, the node that is most likely to experience voltage collapse is identified using a new steady state voltage stability index. Equation 3.46 is used to calculate each node's voltage stability index.The weakest node, or the node with the lowest VSI value, will experience the voltage collapse phenomenon first. In the system in question, the VSI is calculated using the load flow for each bus, and the results are arranged in ascending order. Since the VSIs dictate the order in which the buses are to be taken into consideration for D-STATCOM allocation, all nodes should have their VSIs raised to avoid the risk of voltage collapse.(Nebiyu Yisaye Elias Mandefro, and Belachew Bantyirga, 2020)

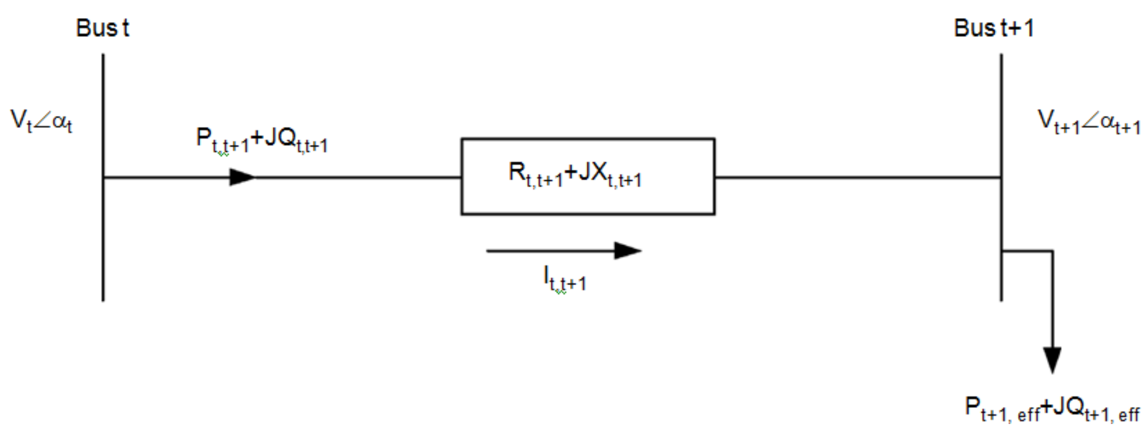

Figure 3.6 Two-bus systems for VSI analysis

$$(t+1) = |V_t|^4 - 4[P_{t+1,} \times X_t - Q_{t+1,} \times R_t]^2 - 4[P_{t+1,eff} \times R_t + Q_{t+1} \times X_t]|V_t|^2 \quad 3.46$$

$$F_3 = \min(VSI(t+1)) \quad 3.47$$

Where: -

F_3: is the voltage stability index's objective function. The voltage stability index at bus t+1 is denoted by VSI (t+1).

t and t+1: are the bus numbers for sending and receiving.

$P_{t+1,eff}$And$Q_{t+1,eff}$: are the relative needs for active and reactive power at bus t+1.

V_t: is the sending bus's voltage.

R_t AndX_t: are branch t's reactance and resistance.

The general objective function (F) can be expressed mathematically as follows:

$$minimize\ (F) = \min\left(W_1 \times F_1 + W_2 \times F_2 + W_3 \times \frac{1}{_3}\right) \qquad 3.48$$

WhereW_1, $W_2$and $W_3$are weighting coefficients that are determined considering the importance

Of the three objectives and also $\sum_{n+1}^{3} W_n = 1$

3.5.2. System Constraint

Voltage deviation limit

The system voltage in all buses should be in an acceptable range

$$V_m^{min} \leq |V_m| \leq V_m^{max} \qquad 3.49$$

The system voltage is constrained with 0.95 ≤ Vm ≤1.05 p.u.

Reactive power compensation

To get the optimum outcome, the size of the distribution static compensator should not be too little or too large in relation to the load value. The following are the minimum and maximum limitations for the reactive power injection into the system via D-STATCOM.

$$Q_{min} \leq Q_{DSTATCOM} \leq Q_{max} \qquad 3.50$$

3.6. PSO Algorithm Parameters

A number of the PSO algorithm's settings can affect how well it performs. Some of these parameter settings and options have a major impact on how effective the PSO technique is for any given optimization problem, while others have little to no impact. (R. Vemana and Dr. M. Sridhar, 2013)

3.6.1 The following are the basic PSO parameters

Swarm Size: The number of particles (n) in the swarm is the population size, often known as the swarm size. A large swarm allows for a more comprehensive coverage of the search space in a single iteration. Using additional particles can reduce the number of iterations required to achieve a satisfying optimization outcome. However, a high number of particles complicates and lengthens the computation for subsequent iterations.

Particle Velocity: is one of the derivative methods of the PSO algorithm. Its value is limited by the borders. The parameters Vmax and Vmin, which indicate which regions between the present and objective locations should be explored, have an impact on the fitness. Because the particles move in greater phases, the answer might not be the best. In a similar vein, if there are insufficient particles, it takes longer for them to enter appropriate solutions.

Random Numbers: The range of uniform random values is [0, 1]. They facilitate the realization of PSO's stochastic behavior.

Inertia Weight: The relationship between the current velocity and the previous velocity is controlled by this control parameter.

Particle Best ($Pbest$): Conceptually, Pbest is similar to autobiographical memory in that each particle remembers its own event. As it travels across the search space, a particle compares its present fitness value to the highest value it has ever achieved at any given time. The term "individual best" or "particle best" refers to the best position that has so far been associated with the highest fitness. Throughout the search, the Pbest of each particle in the swarm can be found and updated.

Global Best ($gbest$): It is the best position achieved thus far among all of the particle Pbests.

Termination Criterion: Following the initial approach, the evaluation steps undergo numerous iterations and objective function restrictions until a stopping requirement is met. Reaching a preset maximum number of repetitions or a particular degree of accuracy in the response are common ways to satisfy the stopping condition.

3.6.2 Procedure for Implementation of Particle Swarm Optimization The PSO approach can be broken down into the following steps

Step 1: Initialization: Construct a population (array) of particles in the problem space with arbitrary locations and velocities on d dimensions.

Step 2: Evaluate the objective optimization fitness function in d variables for every particle.

Step 3: It is necessary to compare the particle's fitness evaluation with its Pbest. If the current value is better than Pbest, set the Pbest location to the current location in d-dimensional space and the Pbest value to the current value.

Step 4: Compare your level of fitness to that of the population as a whole. If the value of the current particle is greater than gbest, gbest is reset to the array index and value.

Step 5: Change the particle's velocity and position using equations 3.51 and 3.52, respectively:

$$V_i^{k+1} = \omega * V_i^k + C_1 * \text{rand1}(Pbest_i - X_i^k) + C_2 * \text{rand2}(gbest_i - X_i^k) \quad 3.51$$

$$X_i^{K+1} = X_i^k + V_i^{k+1} \quad 3.52$$

Where: -

V_i^k: is iteration k's ith velocity component,

X_i^k: is the current position in the ith dimension,

rand: is random number between 0 and 1,

C_1AndC_2 are the acceleration coefficients that are usually set to 2.0,

$Pbest_i$: is the personal best position in the ith dimension,

$gbest_i$: is the global best position in the ith dimension, And ω: is the inertia weight.

Step 6: The iteration counter should be updated.

Step 7: Verify the stopping conditions.

Step 8: If the stopping requirements are satisfied and the most recent particle generated is the PSO's ideal solution, the iteration comes to an end.

Flow charts of the particle swarm optimization for the system

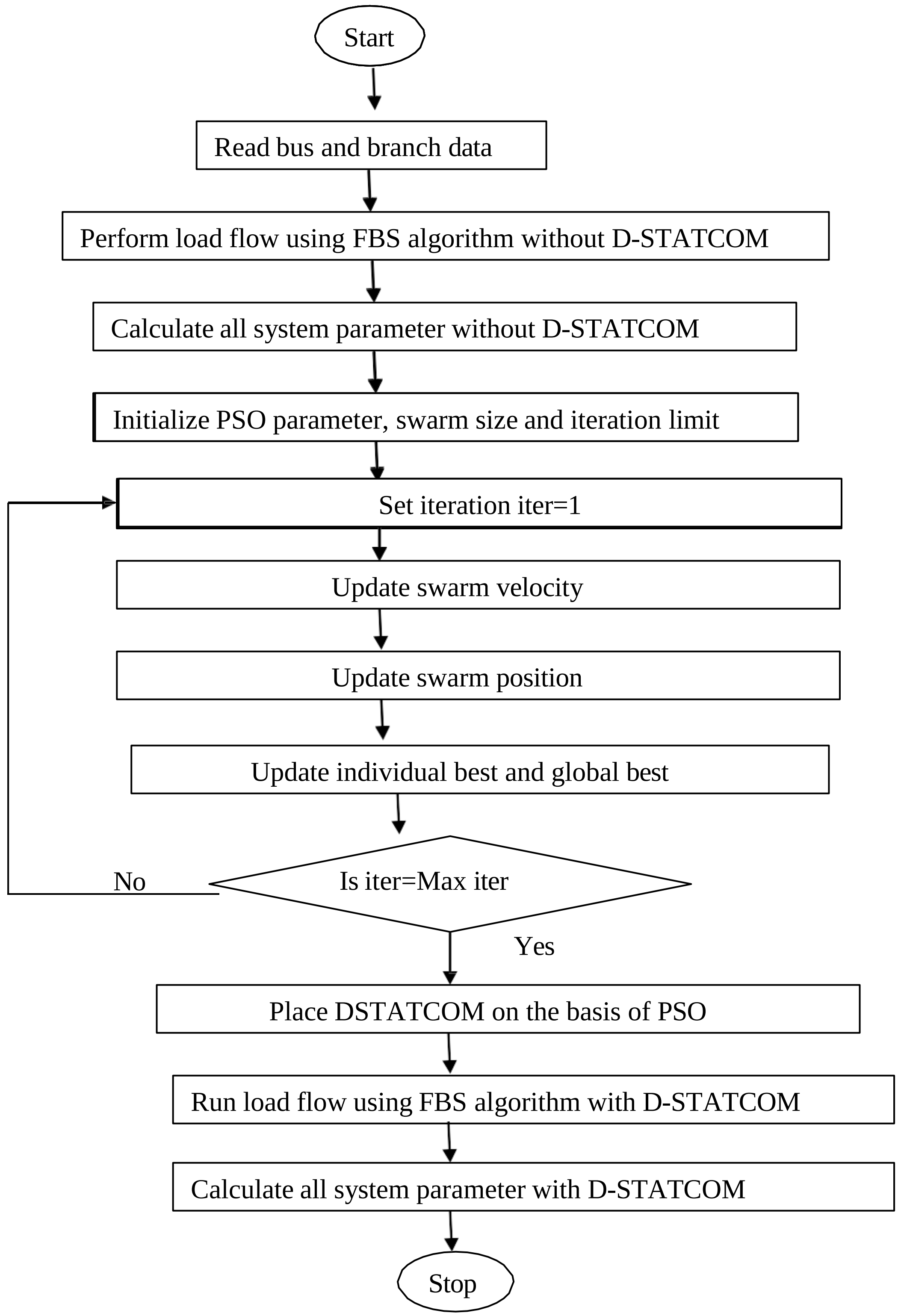

Figure 3.7 Flow charts of the particle swarm optimization for the system

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Introduction

The results and their in-depth discussions are covered in this chapter. They were obtained using the previously constructed algorithm and the data gathered in the previous chapter. The current Bote town distribution network's primary concerns are power losses minimization and voltage profile improvement, with 81 buses in a particular feeder known as Meki-Alemtena. The MATLAB R2015 programming language was used to implement the optimization issue for power losses minimiation and voltage profile enhancement based on the PSO technique.

4.2 System without D-STATCOM Installation (Base Case)

on this instance, backward/forward sweep load flow analysis was used to calculate the voltage profiles at each bus and the active and reactive power losses on each line without the use of any D-STATCOM. The network's base case voltage profiles and matching voltage stability index values derived from the nominal value (1 p.u.) are displayed in Figures 4.1 and 4.4, while Table 4.1 displays the obtained base case power losses. The result shown in Figure 4.1 indicates that the feeder under examination has a minimum voltage of 0.69654p.u. at bus number 81, which is less than the lower threshold limit of 0.95p.u. The load on the line and the distance traveled have an impact on the voltage profile of the feeder. It is evident that voltage drops worsen with increasing feeder length. According to the simulation results, the minimal bus voltage stability index without a compensation device is 0.23537p.u. Low voltage stability could lead to voltage collapse in the radial distribution system, which would cause system disruption. In radial distribution systems, the voltage stability index value should be raised as much as feasible in order to avoid voltage collapse and improve system security. The forward-backward load flow algorithm in MATLAB software is used to calculate the active power loss and reactive power loss in each branch. Under the base case, the system's total real and reactive power losses are 2511.1 KW and 1374.5 kVAr, respectively.

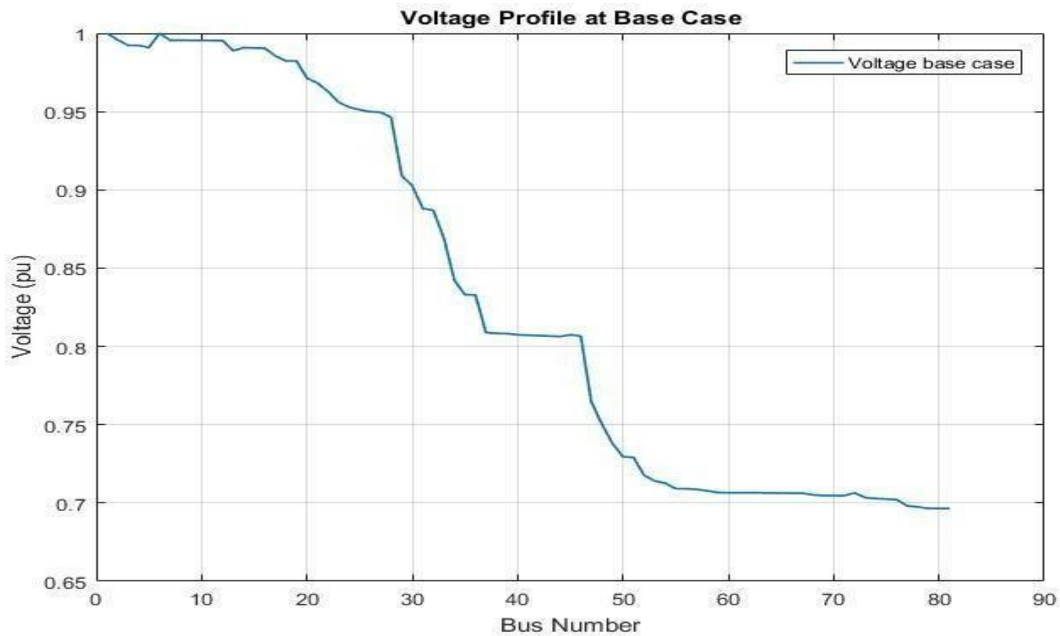

Figure 4.1 Base-case Distribution System Voltage Profile

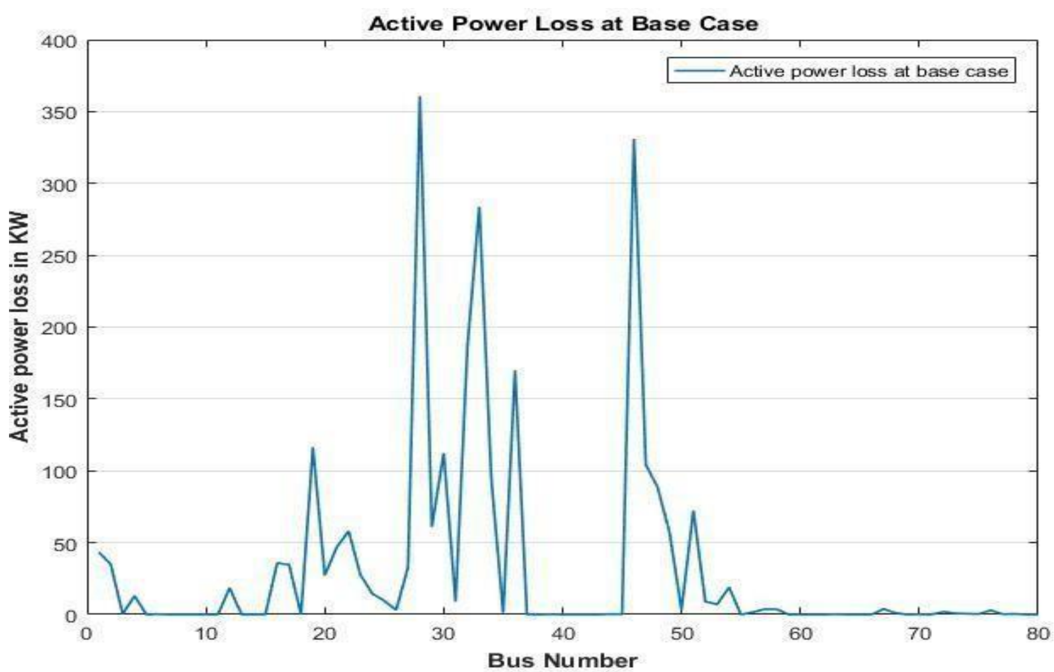

Figure 4.2 Base Case Distribution System Active Power Losses

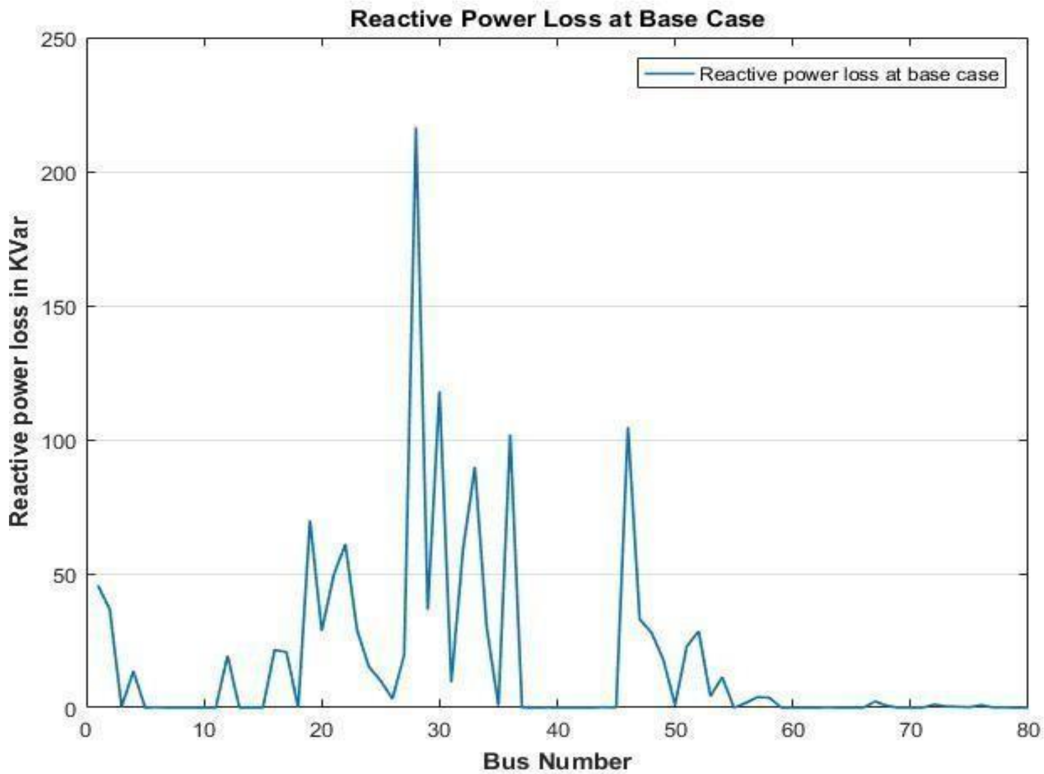

Figure 4.3 Base Case Distribution System Reactive Power Losses

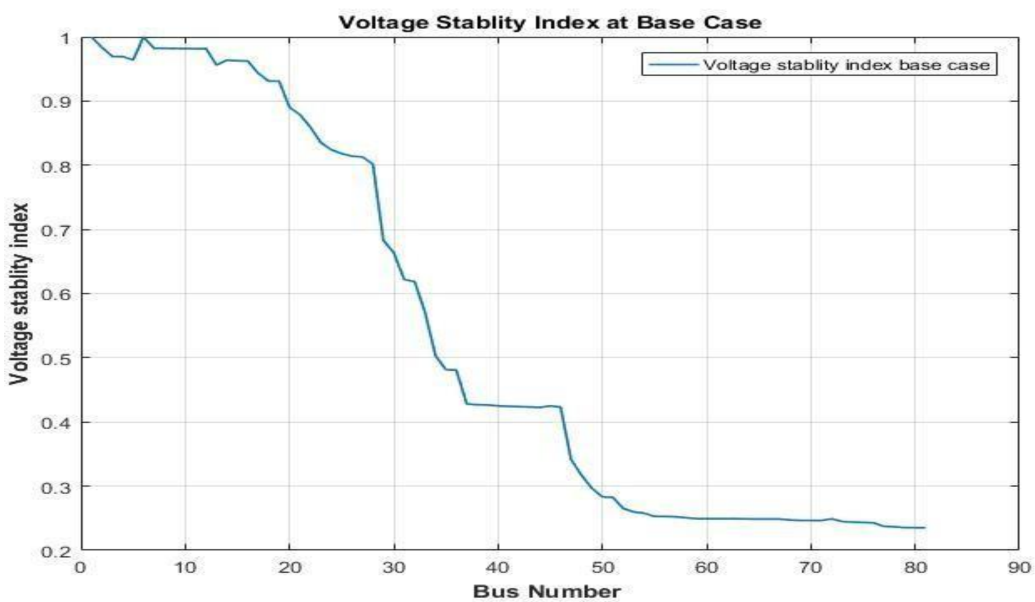

Figure 4.4 Base case Voltage Stability index

Table 4.1 Power Losses in the Base Case

FROM BUS	TO BUS	P_LOSS kW	Q_LOSS kVar	FROM BUS	TO BUS	P_LOSS kW	Q_LOSS kVar
1	2	43.3331	45.5553	41	42	0.0565	0.0339
2	3	34.8468	36.6289	42	43	0.0406	0.0244
3	4	0.3908	0.2299	43	44	0.0576	0.0345
4	5	12.9598	13.6215	37	45	0.3012	0.1758
1	6	0.0017	0.0018	45	46	0.2213	0.0700
2	7	0.2979	0.1787	37	47	330.9938	104.7073
7	8	0.0006	0.0003	47	48	104.1776	32.9781
8	9	0.0434	0.0456	48	49	88.3907	27.9617
9	10	0.0151	0.0159	49	50	56.6946	17.9349
10	11	0.0115	0.0121	50	51	3.2223	1.0193
11	12	0.0021	0.0022	51	52	72.3677	22.8930
5	13	18.4399	19.3908	52	53	9.0171	28.5247
5	14	0.0261	0.0274	53	54	7.0874	4.2512
14	15	0.0846	0.0507	54	55	18.9204	11.3489
15	16	0.0316	0.0190	55	56	0.0091	0.0097
13	17	35.8983	21.5328	55	57	1.7037	1.7915
17	18	34.5821	20.7433	57	58	3.7350	3.9275
18	19	0.0002	0.0001	58	59	3.6548	3.7575
18	20	116.3996	69.8196	59	60	0.0282	0.0296
20	21	27.2630	28.6682	60	61	0.0024	0.0025
21	22	46.7427	49.1518	61	62	0.0032	0.0034
22	23	58.0227	61.0132	62	63	0.0001	0.0001
23	24	27.5608	28.9813	59	64	0.2812	0.1687
24	25	14.5134	15.2614	64	65	0.0149	0.0089
25	26	9.5379	10.0295	65	66	0.0053	0.0032
26	27	3.1506	3.3129	66	67	0.0000	0.0000
27	28	32.8359	19.7306	59	68	3.9027	2.3409
28	29	360.8369	216.4397	68	69	1.0980	0.6586
29	30	60.9161	36.5391	69	70	0.0004	0.0001
30	31	112.2298	118.0141	69	71	0.2186	0.0692

31	32	9.0054	9.4696	59	72	0.0115	0.0069
32	33	186.8080	59.0952	71	73	1.9510	1.1700
33	34	283.7650	89.7668	73	74	0.8660	0.5194
34	35	95.0785	30.0773	74	75	0.5639	0.3383
35	36	1.2484	0.7488	75	76	0.3314	0.1988
36	37	169.9327	101.9303	76	77	3.0466	0.9637
37	38	0.1715	0.1029	77	78	0.2613	0.0826
38	39	0.0462	0.0277	78	79	0.4574	0.1447
39	40	0.2363	0.0747	79	80	0.0255	0.0081
40	41	0.0632	0.0379	80	81	0	0

4.3 System with D-STATCOM Installation

The buses are all in a better voltage profile state, as seen in figure 4.5. However, table 4.2 shows that the network's overall active and reactive power losses are 229.0662KW (with a 90.88% reduction percentage) and 126.5238KVar (with a 90.79% reduction percentage), respectively. Bus number 37's D-STATCOM is 999.8232kVAr, which is its ideal size.

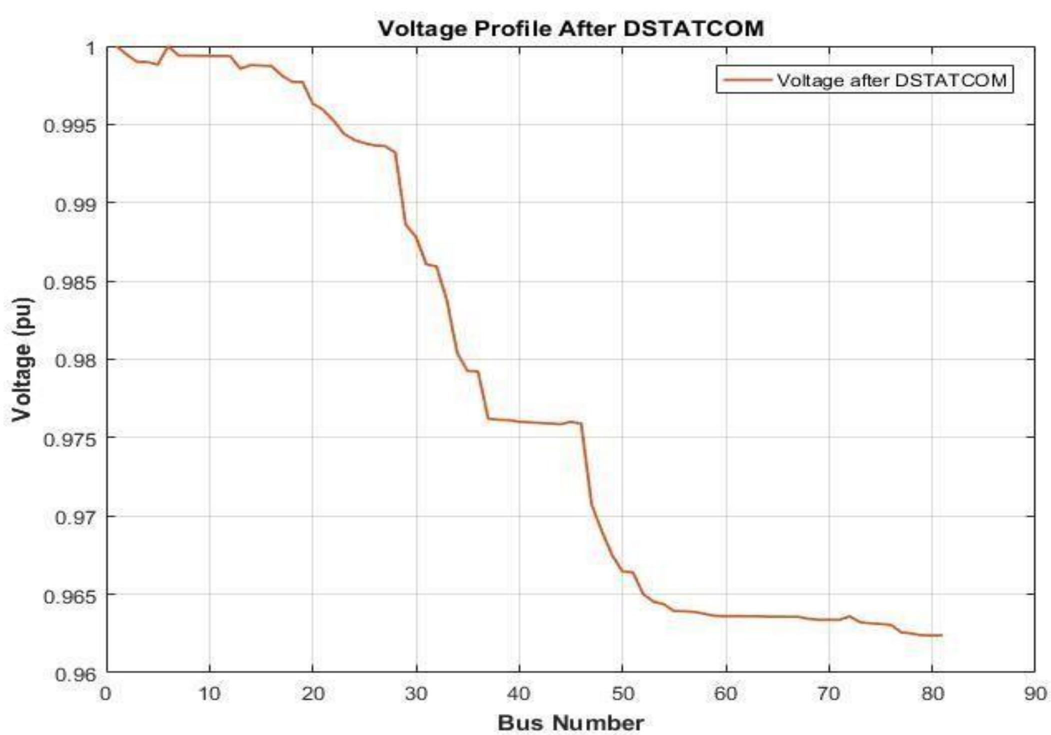

Figure 4.5 Voltage Profile after D-STATCOM Integration

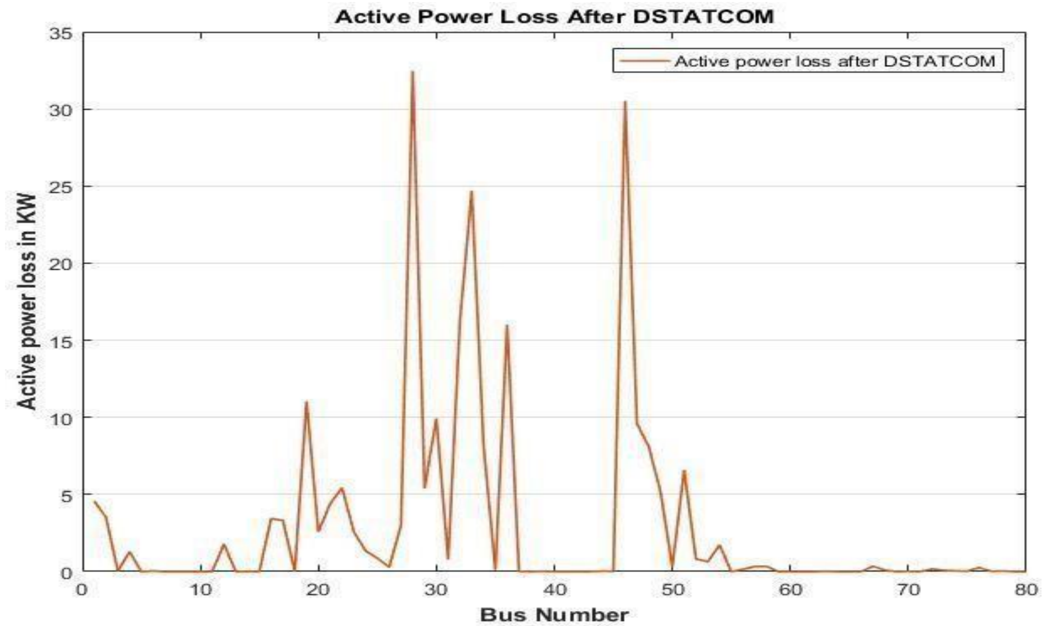

Figure 4.6 Active power loss after D-STATCOM Integration

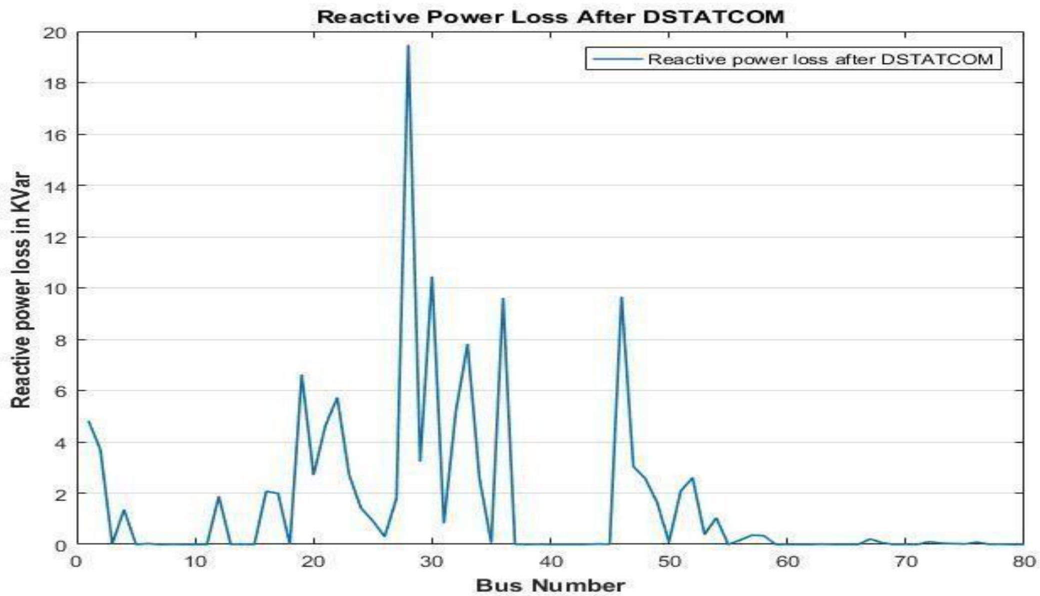

Figure 4.7 Reactive power losses after D-STATCOM Integration

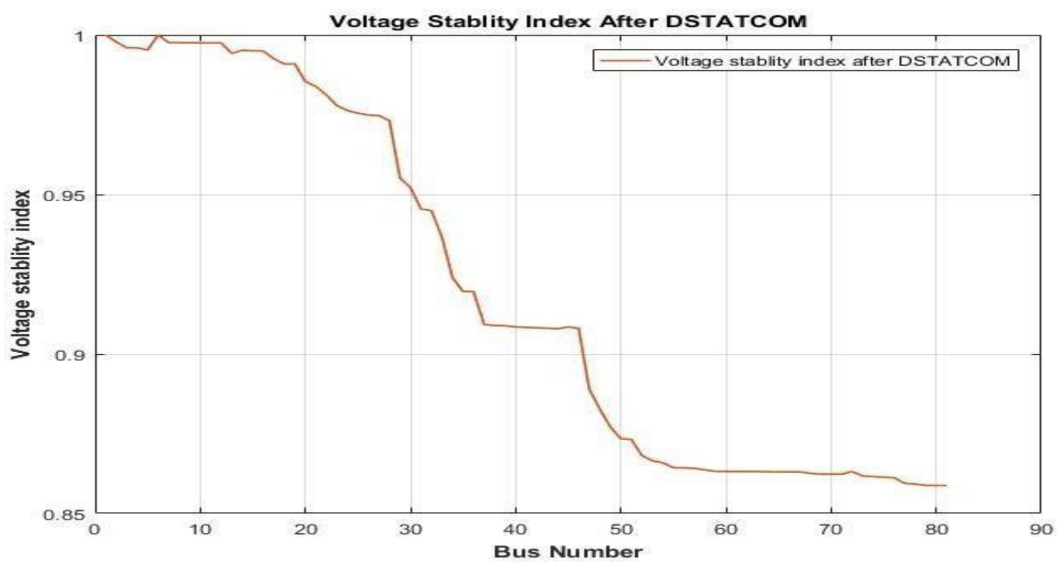

Figure 4.8 Voltage Stability index after D-STATCOM Integration

Table 4.2 Power outages following the installation of D-STATCOM

FROM BUS	TO BUS	P_LOSS kW	Q_LOSS kVar	FROM BUS	TO BUS	P_LOSS kW	Q_LOSS kVar
1	2	4.5792	4.8140	41	42	0.0065	0.0039
2	3	3.5175	3.6974	42	43	0.0047	0.0028
3	4	0.0389	0.0229	43	44	0.0067	0.0040
4	5	1.2880	1.3538	37	45	0.0349	0.0204
1	6	0.0003	0.0003	45	46	0.0256	0.0081
2	7	0.0501	0.0301	37	47	30.5274	9.6571
7	8	0.0001	0.0001	47	48	9.5967	3.0379
8	9	0.0073	0.0077	48	49	8.1114	2.5660
9	10	0.0025	0.0027	49	50	5.1779	1.6380
10	11	0.0019	0.0020	50	51	0.2936	0.0929
11	12	0.0003	0.0004	51	52	6.5884	2.0842
5	13	1.7792	1.8709	52	53	0.8206	2.5960
5	14	0.0043	0.0046	53	54	0.6447	0.3867
14	15	0.0141	0.0085	54	55	1.7208	1.0322
15	16	0.0053	0.0032	55	56	0.0008	0.0009
13	17	3.4466	2.0674	55	57	0.1548	0.1627
17	18	3.3162	1.9891	57	58	0.3391	0.3566
18	19	0.0000	0.0000	58	59	0.3316	0.3409
18	20	11.0368	6.6202	59	60	0.0026	0.0027
20	21	2.5721	2.7047	60	61	0.0002	0.0002
21	22	4.4044	4.6314	61	62	0.0003	0.0003
22	23	5.4400	5.7204	62	63	0.0000	0.0000
23	24	2.5840	2.7172	59	64	0.0257	0.0154
24	25	1.3472	1.4166	64	65	0.0014	0.0008
25	26	0.8710	0.9159	65	66	0.0005	0.0003
26	27	0.2869	0.3017	66	67	0.0000	0.0000
27	28	2.9865	1.7945	59	68	0.3526	0.2115
28	29	32.4591	19.4699	68	69	0.0991	0.0594
29	30	5.3923	3.2345	69	70	0.0000	0.0000
30	31	9.9346	10.4467	69	71	0.0197	0.0062

31	32	0.7846	0.8250	59	72	0.0011	0.0006
32	33	16.2754	5.1486	71	73	0.1755	0.1052
33	34	24.6925	7.8113	73	74	0.0779	0.0467
34	35	8.2013	2.5944	74	75	0.0507	0.0304
35	36	0.1062	0.0637	75	76	0.0296	0.0177
36	37	16.0182	9.6081	76	77	0.2717	0.0860
37	38	0.0199	0.0119	77	78	0.0233	0.0074
38	39	0.0054	0.0032	78	79	0.0407	0.0129
39	40	0.0274	0.0087	79	80	0.0023	0.0007
40	41	0.0073	0.0044	80	81	0	0

4.4 Comparison of Base Case Outcomes with and Without D-STATCOM Integration

As demonstrated in the earlier sections of the base case and D-STATCOM integration, the voltage profile of the feeder under investigation (Meki-Alemtena feeder) had a poor voltage profile with higher voltage deviation values from the nominal value. The bus voltage profile across the feeder has also been improved in the necessary range following the installation of D-STATCOM's optimal size on the right bus, and the minimum voltage profile at bus 81 has improved from 0.69654 p.u. to 0.96266 p.u., which is better than the voltage value obtained prior to D-STATCOM insertion.Figure 4.9 provides a general illustration of this. Similarly, to this, the power losses of the system under testing were higher before the installation of D-STATCOM and significantly decreased by about 90%. The network's overall loss is illustrated in Figures 4.10 and 4.11. Before implementing D-STATCOM, the minimum bus voltage stability index was 0.23537p.u; following D-STATCOM integration, this value increased to become 0.85879p.u. Figure 4.12 provides an illustration of the voltage stability index before and after the D-STATCOM integration simulation result for all 81-bus system buses.

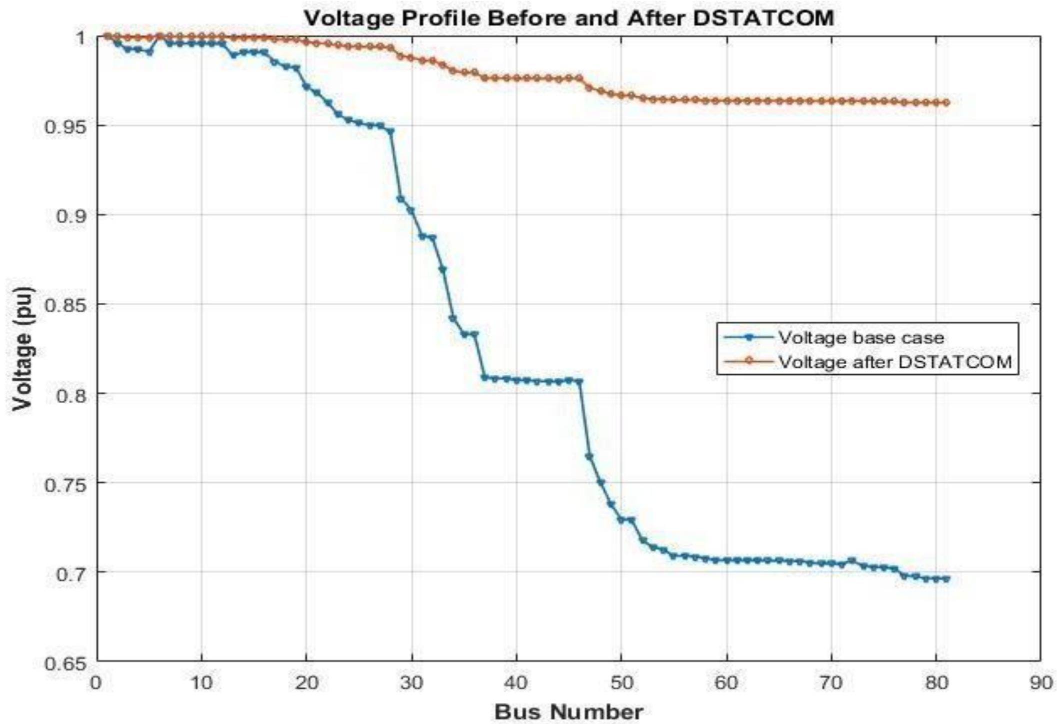

Figure 4.9 Voltage Profile of the System

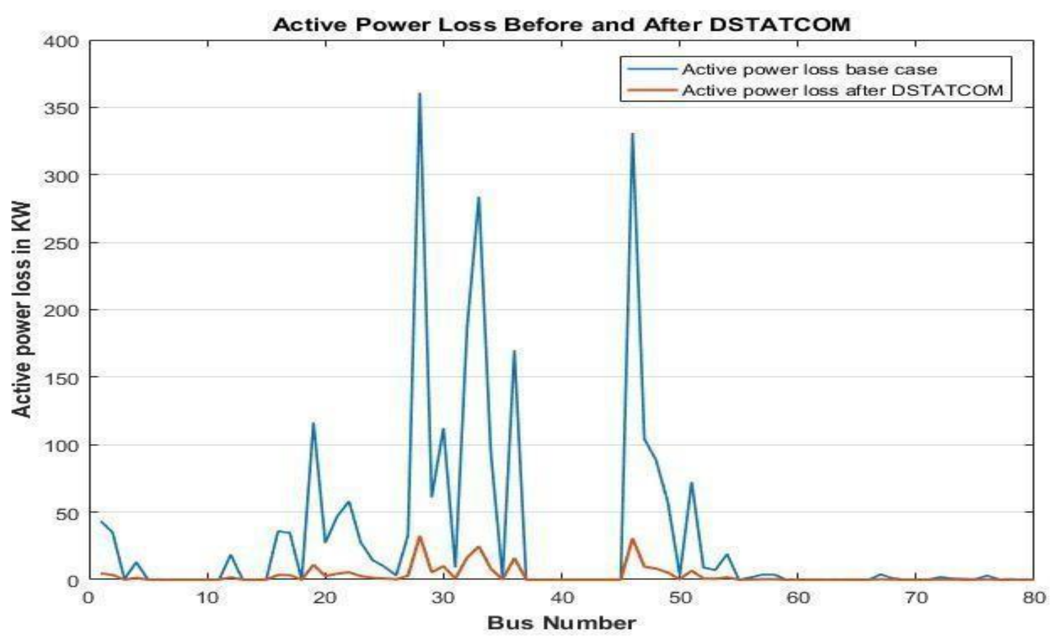

Figure 4.10 Active power Losses of the System

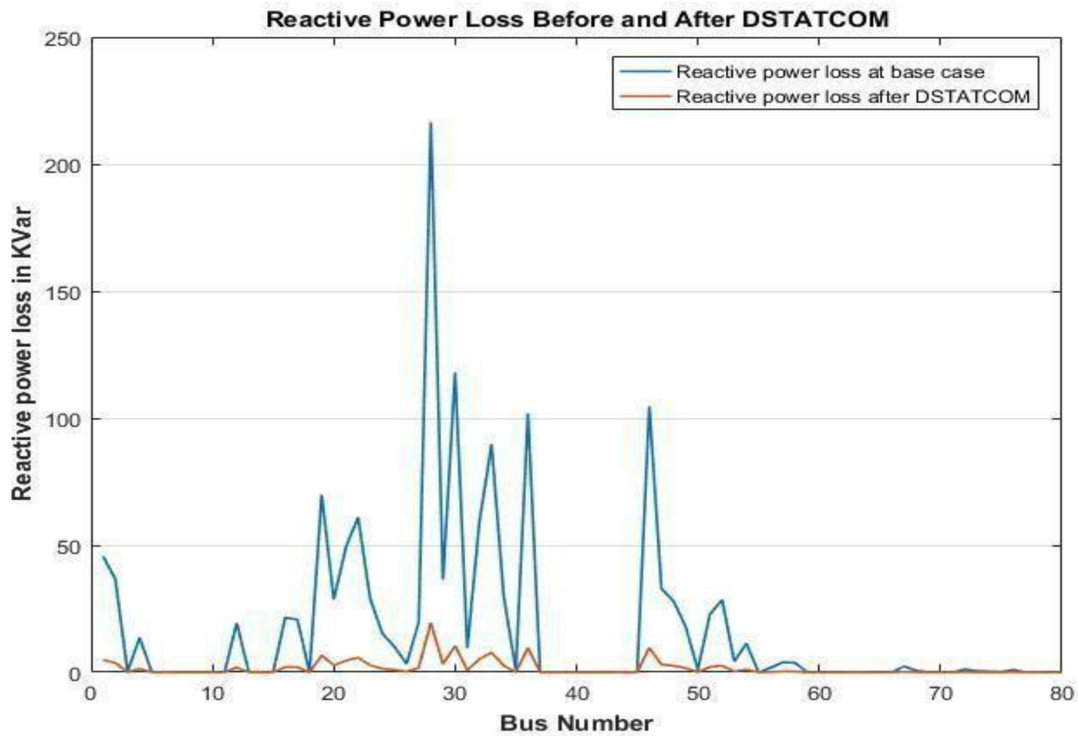

Figure 4.11 Reactive power Losses of the System

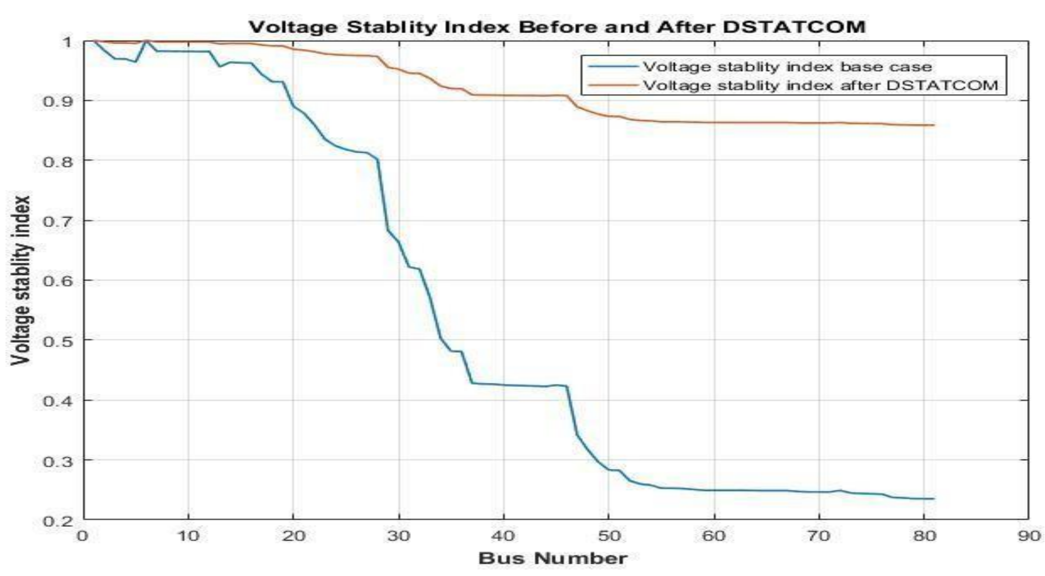

Figure 4.12 Voltage stability index of the System

Table 4.3 Results of the Meki-Alemtena feeder in Bote town summary

PARAMETERS	BASECASE	WITH_D-STATCOM_PSO
Total Power Loss (kW)	2511.0513	229.0662
Voltage Stability Improvement (p.u.)	0.23537	0.85879
Minimum Voltage @ Bus Number	0.69654 @ Bus No 81	0.96266 @ Bus No 81
Maximum Voltage @ Bus Number	1 @ Bus No 1	1 @ Bus No 1
Optimal D-STATCOM Location	NIL	37
Optimal D-STATCOM Size (kVar)	NIL	999.8232

4.5 Cost Analysis

After the size and position of the device are determined, the cost necessary for the successful installation of the D-STATCOM is determined. The cost study started by calculating the total annual energy loss at peak load.

Annual energy loss at base case

Total annual energy loss of Bote town Meki-Alemtena feeder

= Peak power loss (MW)*8760h

= 2.511 MW * 8760 h

= 21.99 GW

Ethiopian Electric Utility's ETB/kWh energy tariffs under the updated power tariff are used to estimate the financial loss. Electricity costs 1829.1 ETB/MWh or 1.8291 ETB/kWh. The entire yearly financial loss due to power outages is estimated using 1829.1 ETB/MWh as follows: **Annual financial loss at base case**

Annual financial loss (ETB) = Total annual energy loss*1829.1 ETB/MWh

=21.99 GW*1829.1 ETB/MWh

= 40.22 million ETB/year

Annual energy loss reduction after D-STATCOM integration

Total annual energy loss reduction of Bote town Meki- Alemtena feeder

= Power loss reduction (MW)*8760h

= (2.511 MW–0.229 MW) * 8760 h

= 19.99 GWh

Annual financial loss reduction after D-STATCOM integration

Annual financial loss reduction (ETB) = Total annual energy loss reduction*1829.1 ETBMWh

= 19.99 GWh*1829.1ETBMWh

= 36.56 million ETB/year

By integrating D-STATCOM with the Bote town Meki-Alemtena feeder, the yearly financial loss from

From 40.22 million ETB to 36.56 million ETB, the annual energy expense decreased by 9.27%. D-STATCOM costs 244 USD per KVAR, which includes installation fees. According to the Commercial Bank of Ethiopia's May 20, 2025, currency rate, 1 USD is equal to 126.0086 ETB.

Analysis of the payback period

Payback period = Net investment/ Net profit

= (Cost in USD*Size D-STATCOM*Exchange Rate)/Net Profit

= (244 USD/KVAR*999.8232 KVAR*126.0086 ETB/USD)/ (36.56 mil.ETB/year)

= 30.74/36.56

Payback period = 0.84 year

According to economic research, the original investment cost's payback period is 0.84 year.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The distribution substation feeder's power losses and voltage drops were the main topics of this thesis. Enhancing the voltage profile and reducing power loss for Bote town with D-STATCOM Meki-Alemtena feeder was the primary focus of this thesis study. Because of its long path, several coupled transformers, and significant load development, the Bote town Meki-Alemtena feeder was chosen as the case study location. This thesis uses the ideal D-STATCOM size and location to solve the maximum power loss, voltage drop, and bus voltage instability that emerge in radial distribution substation feeders. Data collected prior to and following D-STATCOM installation were used in the forward-backward power flow investigation.

Enhancements to the voltage profile and bus voltage stability index were included in the multi-objective function provided to the particle swarm optimization algorithm. Particle swarm optimization was used to determine D-STATCOM's ideal size and placement.

Both with and without D-STATCOM, the system was simulated under full load conditions using a forward/backward load flow technique. The simulation yielded information on the minimum voltage, bus voltage stability index, active power loss, and reactive power loss. Before D-STATCOM was assigned, the Bote town Meki-Alemtena feeder experienced a voltage profile, a minimum bus voltage stability index, total active power loss, and total reactive power loss, according to the simulation's results. They were 2511.1KW, 1374.5KVar, 0.23537p.u., and 0.69654p.u. in that order. The simulation results showed that bus 37 and 999.8232kVAr were the ideal D-STATCOM positioning and size for the feeder, respectively.

This resulted in changes to the minimum voltage, minimum bus voltage stability index, total active power loss, and total reactive power loss to 229.0662KW, 126.5238KVar, 0.96266 p. u., and 0.85879 p. u., respectively. Total active power loss and total reactive power loss both saw percentage decreases of 90.88% and 90.79%, respectively. Finally, based on the findings, it can be concluded that the suggested methodology effectively minimizes power.

loss and improvement of voltage profile for Bote town Meki-Alemtena feeders on the side of customers and perfectly shows the advantage of applying a D-STATCOM in the distribution with a proper placing and sizing algorithm.

5.2 Recommendation and Suggestion for Future work

This research work is beneficial to different parties both directly and indirectly. The direct beneficiaries of this research work are the distribution companies. Some of the direct benefits from this thesis work to the Meki-Alemtena feeder and Ethiopian Electric Utility include;

- This thesis work will help the EEU in reducing both real and reactive power losses in their networks. This reduction in loses will enable them avoid some of the penalties and compensations they incur and hence result to an improvement in their profit margins and their customers as well.
- The thesis work will also ensure that they improve the voltage levels at the consumers to the required limits. This will enable the EEU and EEP to avoid the costs incurred during compensation of spoilt customer equipment due to voltage deviations outside the acceptable limits. As a result, this makes the companies more economical and reliable in operation.
- The work will help the power companies incorporate small-sized green energy sources to their networks easily and more reliably. This is of much importance due to the changing attention in power production with the shifting in green energy.

The following works are suggested to further extend the research carried out in this thesis:

- Further analysis can be conducted by taking into account network reconfiguration with parallel DG and D-SATCOM installation.
- Use different optimization methods like GA, Immune, Gray Wolf, BFOA, and Hybrid GA-PSO to determine the optimal location and size of D-STATCOM.

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APPENDIX

Appendix A 1: Bus and Line data for Bote town Meki-Alemtena feeder

From Bus	To Bus	Conductor Type	R (ohm)	X(ohm)
1	2	AAC95	0.1520905	0.1599292
2	3	AAC95	0.1446865	0.1521436
3	4	AAC50	0.0017355	0.001041
4	5	AAC95	0.056764	0.0596896
1	6	AAC95	0.0330095	0.0347108
2	7	AAC50	0.2314	0.1388
7	8	AAC50	0.0005785	0.000347
8	9	AAC95	0.0687955	0.0723412
9	10	AAC95	0.046892	0.0493088
10	11	AAC95	0.0558385	0.0587164
11	12	AAC95	0.0404135	0.0424964
5	13	AAC95	0.0891565	0.0937516
5	14	AAC95	0.104273	0.1096472
14	15	AAC50	0.380653	0.228326
15	16	AAC50	0.247598	0.148516
13	17	AAC50	0.1764425	0.105835
17	18	AAC50	0.1706575	0.102365
18	19	AAC50	0.241813	0.145046
18	20	AAC50	0.595855	0.35741
20	21	AAC95	0.14191	0.149224
21	22	AAC95	0.244332	0.2569248
22	23	AAC95	0.3085	0.3244
23	24	AAC95	0.1465375	0.15409
24	25	AAC95	0.0799015	0.0840196
25	26	AAC95	0.05553	0.058392
26	27	AAC95	0.01851	0.019464
27	28	AAC50	0.1937975	0.11645
28	29	AAC50	2.20987	1.32554

29	30	AAC50	0.396851	0.238042
30	31	AAC95	0.731145	0.768828
31	32	AAC95	0.0626255	0.0658532
32	33	AAC95	1.2991	0.41096
33	34	AAC50	1.98408	0.627648
34	35	AAC50	0.695609	0.2200504
35	36	AAC50	0.0098345	0.005899
36	37	AAC50	1.9669	1.1798
37	38	AAC50	1.0413	0.6246
38	39	AAC50	0.2805725	0.168295
39	40	AAC50	2.07856	0.657536
40	41	AAC50	0.873535	0.52397
41	42	AAC50	0.780975	0.46845
42	43	AAC50	0.99502	0.59684
43	44	AAC50	1.41154	0.84668
37	45	AAC50	3.84124	2.24162
45	46	AAC50	2.82259	0.892904
37	47	AAC50	4.6059	1.45704
47	48	AAC50	1.47525	0.467
48	49	AAC50	1.34634	0.425904
49	50	AAC50	0.975506	0.3085936
50	51	AAC50	0.060231	0.0190536
51	52	AAC50	1.38177	0.437112
52	53	AAC50	0.175969	0.556664
53	54	AAC50	0.144625	0.08675
54	55	AAC50	0.3904875	0.234225
55	56	AAC50	0.03653705	0.039211
55	57	AAC95	0.0428815	0.0450916
57	58	AAC95	0.104273	0.1096472
58	59	AAC95	0.1138365	0.117036
59	60	AAC95	0.122783	0.1291112
60	61	AAC95	0.0231375	0.02433
61	62	AAC95	0.1267935	0.1333284

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62	63	AAC95	0.0231375	0.0233
59	64	AAC50	0.2238795	0.134289
64	65	AAC50	0.0387595	0.023249
65	66	AAC50	0.3719755	0.223121
66	67	AAC50	0.019669	0.011798
59	68	AAC50	0.3210675	0.192585
68	69	AAC50	0.1232205	0.073911
69	70	AAC50	0.275173	0.0870488
69	71	AAC50	0.036611	0.0115816
59	72	AAC50	1.80492	1.08264
71	73	AAC50	0.432718	0.259556
73	74	AAC50	0.192062	0.115204
74	75	AAC50	0.1463605	0.087791
75	76	AAC50	0.3661905	0.219651
76	77	AAC95	4.0154	1.27024
77	78	AAC95	0.870397	0.2753432
78	79	AAC95	1.52349	0.481944
79	80	AAC95	0.099204	0.0313824
80	81	AAC95	5.69242	1.800752

Appendix A-2 Load data Bote town Meki-Alemtena feeder

Bus	load P(MW)	Load Q(MVAr)	Bus	load P(MW)	Load Q(MVAr)
2	0.16	0.12	42	0.04	0.03
3	0.25	0.189	43	0	0
4	0.04	0.03	44	0.08	0.12
5	0.16	0.12	45	0	0
6	0.16	0.12	46	0.16	0.12
7	0.08	0.06	47	0.04	0.03
8	0.16	0.12	48	0.16	0.12
9	0.16	0.12	49	0.25	0.189
10	0.08	0.06	50	0.16	0.12
11	0.16	0.12	51	0.04	0.03
12	0.16	0.12	52	0.04	0.03
13	0.08	0.06	53	0.08	0.06
14	0.02	0.015	54	0.02	0.015

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15	0.08	0.06	55	0.08	0.06
16	0.25	0.189	56	0.25	0.189
17	0.02	0.015	57	0.16	0.12
18	0.16	0.12	58	0.16	0.12
19	0.02	0.015	59	0.25	0.189
20	0.08	0.06	60	0.08	0.06
21	0.02	0.015	61	0.08	0.06
22	0.08	0.06	62	0.04	0.03
23	0	0	63	0.04	0.03
24	0.16	0.12	64	0.25	0.189
25	0.25	0.189	65	0.25	0.189
26	0.04	0.03	66	0.04	0.03
27	0.02	0.015	67	0.02	0.015
28	0.16	0.12	68	0.25	0.189
29	0.25	0.189	69	0.25	0.189
30	0	0	70	0.02	0.015
31	0.25	0.189	71	0.16	0.12
32	0	0	72	0.04	0.03
33	0.02	0.015	73	0	0
34	0.16	0.12	74	0.08	0.06
35	0.25	0.189	75	0.504	0.378
36	1.25	0.75	76	0.04	0.03
37	0.08	0.06	77	0.16	0.12
38	0	0	78	0	0
39	0.04	0.03	79	0.02	0.015
40	0.04	0.03	80	0.25	0.189
41	0	0	81	0.16	0.12

Appendix B MATLAB Code for Formation of BIBC Matrix

```
Function [bibc_matrix] =BIBC (linedata,busdata)
num_of_lines=length (line data (,2));
num_of_bus=length (bus data(:,1));
From node=line data (,2);
To node=line data(:,3);
connect_matrix_lf=sparse (1:num_of_lines, from node, ones (num_of_lines, 1), num_of_lines, num_of_bus);
connect_matrix_lf=sparse (1:num_of_lines, to node, ones (num_of_lines, 1), num_of_lines, num_of_bus) ;
connect_matrix_lt_lf=connect_matrix_lf+connect_matrix_lt;
connect_matrix_lt_lf1=connect_matrix_lt_lf*connect_matrix_lt_lf;
```


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ቀን፡06/02/2018

የኢትዮጵያ ኤሌክትሪክ ኃይል
ETHIOPIAN ELECTRIC POWER

ለአዳማ ሳይንስና ቴክኖሎጂ ዩኒቨርስቲ

<u>አዳማ</u>

ጉዳዩ፡- መረጃ መስጠጥን ይመለከታል

ከላይ ለመግለፅ እንደተሞከረው ወ/ሮ አለምፀሀይ እርገጤ የተባሉ የዩኒቨርስቲያችሁ ተማሪ በከፍተኛ ደረጃ የሀይል መቆራረጥ ያለበትን የአዳሚቱሉ ሰብስቴሽን ፊደር የሆነውን መቂ-አለምጤና ፊድር ጥናት ለማድረግ ዳታ እንዲሰጣቸው በጠየቁት መሰረት በቀን፡-15/1/2017 ዓ.ም የፊደሩን ሙሉ ዳታ የሰጠናቸው መሆኑን እንገልፃለን።

Adami tulu Substation
incharge

ከሰላምታ ጋር

Appendix B MATLAB Code for Formation of BIBC Matrix

```
Function [bibc_matrix] =BIBC (linedata,busdata)
num_of_lines=length (line data (,2));
num_of_bus=length (bus data(:,1));
From node=line data (,2);
To node=line data(:,3);
connect_matrix_lf=sparse (1:num_of_lines, from node, ones (num_of_lines, 1), num_of_lines, num_of_bus);
connect_matrix_lf=sparse (1:num_of_lines, to node, ones (num_of_lines, 1), num_of_lines, num_of_bus) ;
connect_matrix_lt_lf=connect_matrix_lf+connect_matrix_lt;
connect_matrix_lt_lf1=connect_matrix_lt_lf'*connect_matrix_lt_lf;
```

```
connect_diag_mat=ones (num_of_bus)-eye (num_of_bus);
connect_diag_mat1=connect_matrix_lt_lf1.*connect_diag_mat;
final_connect_mat=triu (connect_diag_mat1);
zero_matrix=zeros (num_of_bus);
zero_matrix1=zero_matrix (:1);
for
ind=1:num_of_bus
node_order_val(:,ind)=sort([zero_matrix1(1:(num_of_bus-...
    length (graph traverse (final_connect_mat, ind)))); ...
graph traverse (final_connect_mat, ind)']);
end
node_order_final=node_order_val;
for
indr=1: length (node_order_final(1,:))
for
indc=1: length (node_order_final(1,:))
order_node=node_order_final (indr,indc);
if (order node>0)
bibc_matrix(order_node,indc)=1;
Bibc_matrix_ord(order_node,indc)=order_node;

if
order_node==0
bibc_matrix(indr,indc)=0;
bibc_matrix_ord(indr,indc)=0;
end
end
end
end
bibc_matrix_ord=bibc_matrix_ord;
```

Appendix C MATLAB Code for Base Case Load Flow

```
function [finalres]=LOAD_FLOW_BASE_CASE
source_num= [1];
[LINEDATA]=LINE_DATA;
BUSDATA=BUS_DATA;
baseKV=15;
baseMVA=100;
PBASE=baseMVA*1000;
VBASE=(baseKV^2)/baseMVA;
busdata_value=BUSDATA;
linedata_value=LINEDATA;
linedata_value(:,4:5)=linedata_value(:,4:5)/VBASE;
resistance_val=linedata_value(:4);
reactance_val=linedata_value(:5);
actual_imped=complex(resistance_val,reactance_val);
busdata_value(:,2:3)=(busdata_value(:,2:3)/PBASE);
imped_value=actual_imped;
[bibc_matrix] =BIBC (linedata_value, busdata_value);
bibc_matrix(source_num,:)=[];
bibc_matrix(:,source_num)=[];
final_bibc_matrix=bibc_matrix';
final_bibc_matrix=final_bibc_matrix'*diag(actual_imped);
final_dlf_matrix=final_bcbv_matrix*final_bibc_matrix;
complex_load_d=complex(busdata_value(:,2),busdata_value(:,3));% complex power load
complex_load_g=zeros(size(busdata_value,1),1);
final_load_matrix=(complex_load_d-complex_load_g);
final_load_matrix (length(source_num))=[];
initial_volt_value=ones(size(busdata_value,1)-length(source_num),1); % initial bus voltage
voltage_drop_value=initial_volt_value;
max_iter=100;
for
```

```
ind_lop=1:max_iter
%backward sweep
inject_current_data=conj(final_load_matrix./voltage_drop_value); % injected current at each
bus
    IB=final_bibc_matrix*inject_current_data; %get the cumulative injected current flowing
through each branch
old_volt=voltage_drop_value;
volt_drop_each=final_dlf_matrix*inject_current_data; %voltage drops along each branch.
voltage_drop_value=initial_volt_value-volt_drop_each;
    old_volt1=(old_volt);
new_volt=(voltage_drop_value);
error_volt_tolr=max(abs(old_volt1-new_volt));
end
final_volt_data=[ones(length(source_num),1);voltage_drop_value];
Locvoltm=find(final_volt_data>1);
final_volt_data(locvoltm)=1;
from_node=linedata_value(:,2);
to_node=linedata_value(:,3);
forind=1: length(from_node)
    volt_diff_value (ind, :)=final_volt_data(from_node(ind))-final_volt_data(to_node(ind));
end
volt_diff_value1=abs(volt_diff_value);
ploss=((volt_diff_value1.^2).*resistance_val)./(abs(imped_value).*abs(imped_value))*10^5;
% Each Line Loss in kWs
loc1=find(~(isnan(ploss)));
qloss=((volt_diff_value1. ^2). *reactance Val). /(abs(imped_value).*abs(imped_value))*10^5;
% Each Line Loss in kVAr
loc2=find(~(isnan(qloss)));
total_power_loss=sum(ploss(loc1));
finalvoltage=real(final_volt_data);
```

```
f1=total_power_loss;
f2=sum((1-finalvoltage).^2);

%% vsi calculation
for kk=1: length(busdata_value(:,2)) forki=1:
length(linedata_value(:,4))
        vsival(kk)=(abs(finalvoltage(kk)). ^4) -(4*(busdata_value(kk,2) *linedata_value(ki,4)-
busdata_value(kk,3)*linedata_value(ki,5)).^2)-((4*(busdata_value(kk,2)*linedata_value(ki,5)-
busdata_value(kk,3)*linedata_value(ki,4)).^2)*finalvoltage(kk).^2);
end end

f3=min(vsival); w1=0.3;
w2=0.3; w3=0.4;
final_obj=w1*f1+w2*f2+w3*(1/f3);
finalres{1}=final_obj;
finalres{2}=total_power_loss;
finalres{3}=finalvoltage;
finalres {4}=f2;
finalres {5}=min(vsival); finalres
{6}=ploss; finalres{7}=qloss;
finalres{8}=vsival; P_LOSS_kW=ploss;
Q_LOSS_kVar=qloss;
FROM_BUS_NODE=from_node;
TO_BUS_NODE=to_node;
RESULT=table (FROM_BUS_NODE,TO_BUS_NODE,P_LOSS_kW,Q_LOSS_kVar);
Finalres {20}=RESULT;
```

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