Optimal Sizing and Placement of Distribution Static Compensator for Improvement of Distribution Feeder Loss and Voltage Profile (Case Study: Debre Berhan Distribution System)

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A Thesis Submitted to the Department of Electrical Power and Control Engineering (Power System Engineering)

School of Electrical Engineering and Computing

Office of Graduate Studies

Adama Science and Technology University

September, 2023

Adama, Ethiopia

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DECLARATION

I declare that this thesis entitled **"Optimal Sizing and Placement of Distribution Static Compensator for Improvement of Distribution Feeder Loss and Voltage Profile (Case Study: Debre Berhan Distribution System)"** is my work and has not been submitted to any university for a similar purpose. The references used in this thesis are duly recognized by proper citations.

Helen Tsegay	________________	________________
Name of student	Signature	Date

RECOMMENDATION OF ADVISORS

I the major advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled **"Optimal Sizing and Placement of Distribution Static Compensator for Improvement of Distribution Feeder Loss and Voltage Profile (Case Study: Debre Berhan Distribution System)"** which was prepared under my guidance by **Helen Tsegay** submitted in partial fulfillment of the requirements for the degree of Master's of Science in Electrical Power and Control Engineering, Postgraduate in Power System Engineering. Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Dr. Milkias Birhanu	____________________	________________
Major Advisor/Supervisor	Signature	Date

APPROVAL SHEET

I, the advisor of the thesis entitled **"Optimal Sizing and Placement of Distribution Static Compensator for Improvement of Distribution Feeder Loss and Voltage Profile (Case Study: Debre Berhan Distribution System)"** developed by **Helen Tsegay,** hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Milkias Birhanu	____________________	________________
Major Advisor/Supervisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis have read and evaluated the thesis entitled **"Optimal Sizing and Placement of Distribution Static Compensator for Improvement of Distribution Feeder Loss and Voltage Profile (Case Study: Debre Berhan Distribution System)"** and examined the candidate during the 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, Postgraduate in Power System Engineering.

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Finally, approval and acceptance of the thesis are contingent upon the submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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ABSTRACT

The demand for electricity has increased significantly in the last few years but the existing distribution feeders are unable to provide the additional power in a safe and reliable manner due to various problems. The main problems that indicate the distribution system performance are high frequency and duration of power interruptions, poor voltage profile, and power loss. In this research work, a Distribution Static Compensator (D-STATCOM) is integrated with the existing radial distribution system to address the above-mentioned problems. The optimal size and appropriate location of the D-STATCOM is determined using the Dragonfly Algorithm (DA). The proposed system was tested on the Aliyu-amba feeder in the Debre Berhan Distribution System and the load flow analysis was done using the Forward-Back Sweep (FBS) load flow method. The total active and reactive power losses of the base-case power flow result are 1079.779 KW and 693.528 KVAR respectively. In addition, out of 193 total buses, 130 buses are below the acceptable voltage limit. After the integration of D-STATCOM with the distribution system, the minimum is voltage improved from 0.84022 p.u to 0.95066 p.u and the voltages of all the buses are above the minimum value (i.e. 0.95 p.u). In addition to this, the active and reactive power loss reduction percentages are 45.916% and 45.621% respectively. Finally, the cost-effectiveness of the required size of D-STATCOM was analyzed and the payback period was about two years.

Keywords: *Dragonfly Algorithm, D-STATCOM, Forward-backward sweep, Power loss, Radial distribution system, Voltage profile improvement*

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ABBREVIATIONS

A.C	Alternate current
AAC	All Aluminum Conductors
BIBC	Bus Injection to Branch Current
BCBV	Branch Current to Bus Voltage
CEL	Cost of Energy
COA	Coyote optimization algorithm
DA	Dragonfly Algorithm
DC	Direct current
DLF	Direct Load Flow
DG	Distribution generation
DO	Dragonfly Optimization
D-FACTS	Distribution flexible alternating current transmissions
DORM	Dragonfly optimization reconfiguration method
R-FACTS	Flexible Alternating Current Transmissions
DS	Distribution system
D-STATCOM	Distribution static compensator
DVR	Dynamic voltage regulator
E	East
E_C	Energy cost rate
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
ENS	Energy not supplied

ETB	Ethiopian Birr
FACTS	Flexible Alternating Current Transmissions
FBS	Forward/Backward Sweep
GA	Genetic Algorithm
GSA	Gravitational search algorithm
GWO	Grey wolf optimization
IEEE	International of Electrical and Electronics Engineers
IPFC	Interline power flow controller
k	iteration counter
KVAR	Kilovolt Ampere Reactive
KVA	Kilovolt Ampere
KCL	Kirchhoff's Current Law
Km	Kilometer
KVL	Kirchhoff's Voltage Law
KV	Kilovolt
KW	Kilo Watt
MATLAB	Matrix laboratory
MFO	Moth Flame Optimization
MW	Mega Watt
MVAr	Mega volt Ampere
N	North
NR	Network reconfiguration
NVD	Net voltage deviations

PSO	Particle swarm optimization
PCC	Point of common coupling
p.u	Per unit
RDS	Radial distribution system
SF	Sensitivity factor
STATCOM	Static Synchronous Compensator
SVC	Static var compensator
SSSC	Static synchronous series compensator
T	Time
TSCS	Thyristor-controlled series capacitor
TSSC	Thyristor-switched series capacitor
UPFC	Unified power flow controller
UPQC	Unified power quality conditioner
USD	United states dollar
V	Volt
VDI	Voltage Deviation Index
VSC	Voltage source converter
VSI	Voltage Stability Index
W	Weight factor
WOA	Whale Optimization Algorithm

CHAPTER ONE

INTRODUCTION

1.1. Background

An Electrical power system is an interconnection of three main components such as generation, transmission, and distribution systems. The generation station generates a bulk of electrical power from other forms of energy sources such as thermal, hydropower, wind, solar, or nuclear. In Ethiopia, the great majority of electrical power produced by power plants is a hydroelectric system. The generation stations are connected to the substation via high-voltage transmission lines.

The distribution system is responsible for delivering electrical power from the transmission system to the consumers, and it is often characterized by high resistance and impedance, which results in significant energy losses and voltage deviations. The distribution system consists of overhead and underground cables, which distribute electrical energy to the end users with the required voltage level(Of et al., 2018). Distribution lines are normally shorter than transmission lines and carry a smaller amount of power. Among the main components of the power system, the distribution system is the most complex and faces different problems. The majority of the distribution system is radial due to its simplicity and lower cost. A radial current distribution system is passive, meaning that power flows in one direction from the source to the final node. A high R/X ratio in a radial distribution network results in poor voltage stability, large power loss, and high voltage drop (Alam, 2018; Salkuti, 2022). The main distribution system issues that indicate performance include a high frequency and duration of interruptions, a poor voltage profile, and power loss (A. Hussain, 2021). Each problem described above has its reason for happening, for example, power loss can be technical and non-technical losses. Technical losses happen due to the physical properties of the power system's infrastructure and equipment, such as I^2*R or copper loss in conductor cables, wires, transformers, switches, and generators. Non-technical losses are losses due to human errors or external actions and social issues. Other reasons are the length and loading condition of the feeder, the types of load connected to the system, and the radial nature of the feeder(Mitiku Teferra & Ngoo, 2021; Urinboy & Hasanov, 2021).

There are two options to improve the performance of the distribution system: The first option is building a new power plant to meet the power demand. However, this option is costly and time-consuming. The second option is the addition of compensating devices to the existing system. This option is the most economical and convenient. Therefore, the most common methods used for improving the performance of the existing distribution system are network reconfiguration, integration of Distributed generation, capacitor placement, and integration of FACTS devices (Rudresh et al., 2012; Mitiku Teferra & Ngoo, 2021).

Network reconfiguration is done by using tie and sectionalized switches to minimize the reliability indices, the system's power loss, and load balancing in the distribution system. Distributed generation is a small-scale generation that is close to the load center and feeds active, reactive, or both into the distribution system. FACTS controller is a power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability. To maximize the utilization of FACTS devices and enhance network performance, finding their optimal allocation and sizing is very necessary. Since inappropriate sizing and placement of reactive compensators in the network will increase the costs of power losses, energy production, and power transmission(Noori, 2021). There are different approaches used for determining the optimal placement and size of FACTS devices. These are analytical approaches, conventional optimization techniques, meta-heuristic optimization techniques, and hybrid methods.

Most optimization techniques are too sophisticated and suffer from premature convergence and loss of accuracy. However, metaheuristic optimization techniques are simple to describe, use multi-objective functions, and consider many constraints when compared to other methods. Those optimization techniques can be used to find the best location and size of different FACTS devices simultaneously (Ahmad & Sirjani, 2019; Mustapha & Salvadorinho, n.d. 2017).

1.2. Statement of the Problem

Due to increasing the number of population size, industries, and nearby cities expansion in Debre Berhan town; the power demand in the Debre Berhan distribution system has been increasing from time to time. To meet the power demand, the radial distribution feeders that transport electricity from the substation to the customers are overloaded beyond their carrying capacity. This results in high power losses, voltage drops, damage to electrical equipment, and reduced efficiency of the feeder. This study confirmed that the active and reactive power losses of the Aliyu-amba feeder are 1079.779 KW and 693.528 KVAR respectively and the voltage profile of 130 buses are below the acceptable minimum voltage limit (0.95p.u). This weak voltage profile leads to voltage instability/blackout in the system. Therefore, there is a great need for a scientific solution in the selected feeder to improve the voltage profile and reduce power loss. Such as network reconfiguration, capacitor placement, integration of DG and D-FACTS devices. However, integration of D-STATCOM has several advantages over other methods. This makes it necessary to integrate the D-STATCOM in an optimal location and size using the Dragonfly algorithm to meet the technical and economic needs of the system.

1.3. Objective of the Study

1.3.1. General Objective

The main objective of this thesis is optimal sizing and placement of distribution static compensator for improvement of distribution feeder loss and voltage profile.

1.3.2. Specific Objectives

The specific objectives of the thesis are described here:

- ✓ To perform load flow analysis for the existing system
- ✓ To determine the optimal location and size of D-STATCOM using Dragonfly Algorithm
- ✓ To increase distribution feeder efficiency by design of D-STATCOM in the selected feeder
- ✓ To compare the simulation results of the proposed system with and without D-STATCOM
- ✓ To perform cost analysis for the integration of D-STATCOM

1.4. Significance of the Study

The principal importance of this study is to improve the voltage profile and reduce power loss to enhance the performance of the distribution system. Since the power loss increases the electric utility's bills and decreases the voltage profile of certain buses out of the acceptable limit will cause a total voltage collapse/blackout. Therefore, by integrating D-STATCOM with the distribution system, this thesis has significant implications for reducing such issues in the selected area.

1.5. Methodology

To attain the above objectives of the study, the following research methods will be followed

Literature review: The literature review evaluates different techniques used for power loss reduction and voltage profile optimization of distribution systems and includes reading various journals, books, articles, and unpublished papers.

Data collection: The real data required for this study will be gathered by using primary and secondary data collection. The primary data are collected by measurement of some parameters, observation of recorded data, and interviews with concerned bodies, whereas the secondary data are collected from data sheets, a literature and use a mathematical formula for the generation of some data from primary data. The relevant data for this study are line data, bus data, interruption data, network base voltage, conductor sizes, transformer ratings, and the layout of the feeder.

Data analysis: After gathering, the data will be analyzed and put in an appropriate format for use.

System modeling and load flow analysis: Using the data gathered, the base case network model will be created. Because of the high *R/X* ratio in the distribution system, the traditional load flow methods (i.e. Newton Raphson, Guess Sedial, Fast decoupled) have slow convergence rates and they are complex. The Forward-Backward sweep distribution load flow method will be used to determine the base case power losses and the voltage profile. Since this load flow method is simple and works on the principle of Kichiff's laws (i.e. KVL and KCL).

Problem formulation: It includes system constraints and objective function formulation. Determining the objective function, which is subjected to minimize both the real and reactive power losses and the voltage deviation.

Result analysis: After obtaining the optimal size and appropriate location of the D-STATCOM, the voltage profile and power loss results are compared with the base case results of the network.

1.6. Scope of the Study

The study targets power loss minimization and voltage profile enhancement of distribution feeders by optimal sizing and placement of D-STATCOM using dragonfly optimization. However, the effect of D-STATCOM on harmonics is not included in this study.

1.7. Organization of the Thesis

The overall contents of this thesis are organized into five chapters and are briefly outlined below.
Chapter one discussed a brief introduction to the background of the thesis, a statement of the problem, objectives, scope, description of the methodology, and outline of the thesis.

Chapter two explained the theoretical background of the distribution system and reviews various literature on power loss reduction, voltage profile improvement, and optimization techniques in the distribution system.

Chapter three details data collection and analysis, system modeling, and methods proposed to reduce power loss and improve the voltage profile of a radial distribution system.

Chapter four presented simulation results, discussion, and comparative analysis of the system with and without D-STATCOM placement.

Chapter five presented conclusions, recommendations, and future work of the thesis.

CHAPTER TWO

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1. Literature Review

To reduce the power loss in the distribution system and improve the voltage profiles, several researchers have implemented different methods. The reviewed articles related to the present work are presented as follows.

(Abhiraj, 2017) presented Dragonfly Optimization has been applied to reconfigure the distribution networks to improve the Voltage Profile by minimizing the net voltage deviations (NVD) without causing any thermal violations, while retaining the radial structure. This DO optimally selects the open- switches based on a fitness function built from the problem objective function and constraints. The system was tested on 33 and 69-node distribution systems and the proposed DORM can provide an enhanced Voltage profile on two test systems without any extra infrastructural facilities. The results of the DORM have been compared with those of the BBO, GA, and PSO-based methods. The suggested method is suitable for practical application on networks of any size. However, the paper didn't include power loss minimization in the objective function.

(Balakumar et al., 2021) proposed to improve voltage characteristics and reduce losses in distribution networks using the Flame Moth algorithm. In this paper, Moth Flame Optimization (MFO) and Particle Swarm Optimization (PSO) are used to determine the correct size and location of Static Var Compensation (SVC) to improve the voltage profile and minimize power loss in the distribution network. The proposed system was tested on a 34-bus system in Wolaita Sodo. Minimizing both active and reactive power loss as well as voltage deviation reduction are included in the objective function formulation. Based on the results, the authors concluded that the applied MFO algorithm shows a lower power loss value than the reported literature results and the PSO algorithm. By placing SVCs where more reactive power is required for voltage stability, the voltage profile of the system is greatly improved. However, the cost analysis of SVC integration was not studied.

(Noori, 2021) reviews the multi-objective optimal sizing and placement of D-STATCOM in a radial distribution network. The Whale Optimization Algorithm (WOA) is used to find the optimal size and location of the D-STATCOM, and the objective function includes voltage profile optimization, power loss reduction, and network reliability considering various dynamic loads with a weighting method. The proposed system has been tested on IEEE 33-bus and Ahvaz 59-bus distribution networks. Nevertheless, reactive power loss reduction is not included in the objective function.

(Amin, 2019) proposed a review of Hybrid Analytical–Coyote Optimization for Optimal Placement of Distribution Static Compensators in Radial Distribution Systems. The main goal is to minimize real power losses and improve the voltage profile while taking operational constraints into account. An analytical technique is used to find the exact dimensions of the D-STATCOM, while the location is determined by the COA. The system was proposed on IEEE 33 and 69 buses and the results show that the proposed hybrid analytical COA is more effective in adequately compensating reactive power to reduce active power loss compared to other existing techniques. However, this analysis did not include cost analysis and reactive power loss.

(Arya & Loss, 2019) proposed that the Gravitational Search Algorithm (GSA) to determine the exact location of the distributed static compensator (D-STATCOM) for minimizing power loss, voltage profile index, and enhancing the voltage profile and the annual energy savings for the distribution network. Finally, the performance of the proposed algorithm was tested on IEEE 33 and IEEE 69 bus systems, and the performance of GSA is compared with other techniques like the immune algorithm, bat algorithm, and sensitivity approach method for optimal allocation of D-STATCOM. It can be seen that the proposed method achieves the best results. Nevertheless, cost analysis and payback period are not included.

(Kumar et al., 2018) introduced a Network Reconfiguration algorithm for minimizing power losses and reliability enhancement of the radial distribution system with the integration of Distributed Generation. SF method is adopted for the best combinations of switches as well as placement of DG for minimization of losses, and the cutest approach is used for reliability enhancement. The proposed algorithm was implemented for the IEEE 33-bus radial distribution system. IEEE 33-Bus RDS Base configuration with DG Installation and Reconfiguration of the system with DG Installation cases are analyzed with MATLAB Programming. The results show that Network reconfiguration showed better results than the base configuration with the installations of DG. The impact of DG locations on the reduction of power loss has been obtained. The improvement of reliability from base case to NR case, base case to the base with DG, and NR case to NR case with DGs were observed. The cost analysis and payback period of the DG did not perform.

(Benalia et al., 2020) reviews the reduction of power loss and improvement of voltage characteristics by precisely determining the optimal location and size of distributed generation based on three indices, namely Index Vector Method (IVM), Voltage deviation index (VDI) and voltage stability index (VSI). The GWO, WOA, and PSO algorithms were used to find the optimal DG size. In this paper, DGs operating with a unit power factor and DGs operating with a lagging power factor were considered for the analysis. The proposed system has been tested on IEEE 33 and 69 bus radial distribution systems. The authors concluded that DG with a lagging power factor provides better results than DG with a unity power factor and that the three algorithms produce very similar values. In this paper, the cost analysis of DG integration was not studied.

(Jayabarathi et al., 2022) presented an Optimal Capacitor Placement for minimizing the cost of capacitor installations and total real power loss in radial distribution systems. The hybrid grey wolf optimizer (HGWO) is used to determine both the optimal size and location of the capacitors. The proposed system has been tested on IEEE 34-, 69-, 119 bus RDSs and a practical 22-bus radial distribution system. The author concluded that HGWO performs very well, and it is a highly suitable optimization method for solving optimal capacitor placement problems. Nevertheless, voltage profile improvement and reactive power loss minimization were not included in the objective function.

(Salkuti, 2022) reviews the optimal allocation of DGs and D-STATCOMs with network reconfiguration in a radial distribution system for minimizing the power losses and enhancing the system voltage. The system is tested on IEEE 33 bus system and GSA is used to determine the best location of DGs and D-STATCOMs. Based on the generated simulation results, the network loss has significantly decreased and the system voltage profile has improved. However, the cost analysis for the integration of D-STATCOM and DG was not performed.

Most of the proposed algorithms consider single objective functions, low convergence rate algorithms, and ignore reactive power losses and cost analysis in their formulation. To fill the gaps in previous works, this research work includes reactive power losses in the objective function formulation, considers multi-objective function, and uses a fast convergence rate algorithm. In addition to this, a cost analysis for D-STATCOM integration was also conducted.

2.2. Electrical Distribution System Background

An Electrical distribution system is one of the power system's components; which distributes electric power to different small and big consumers with a required voltage level through a distribution network. Generally, any distribution system consists of substations, feeders, distribution transformers, distributors, and main services(Module et al., n.d.; V K Mehta, 2006).

Substation: A distribution substation is one type of electrical substation; that is used to transform electricity from a higher voltage to a lower that can be used by consumers.

Distribution feeder: A distribution feeder is a set of electrical conductors that carry electricity from a distribution substation to homes and businesses. The current in the feeder stays constant because no tappings are taken from it. The primary factor taken into account while designing a distribution feeder is the current carrying capacity.

Distributors: are conductors from which tappings are taken to provide for the consumers. In a distributor, tappings are taken at many locations along its length. As a result, the current flow through a distributor is not constant. The voltage drop across a distributor's length is the primary factor to be taken into account during its design.

Service mains: are generally small cables that are used to link the distributor and consumer terminals.

Distribution transformer: It is used to step down the primary distribution voltage levels (33/15KV) to the secondary voltage levels (380/220V) used by customers in their homes, businesses, and commercial buildings (V K Mehta, 2006). It also provides protection for the electrical system from overloads and short circuits.

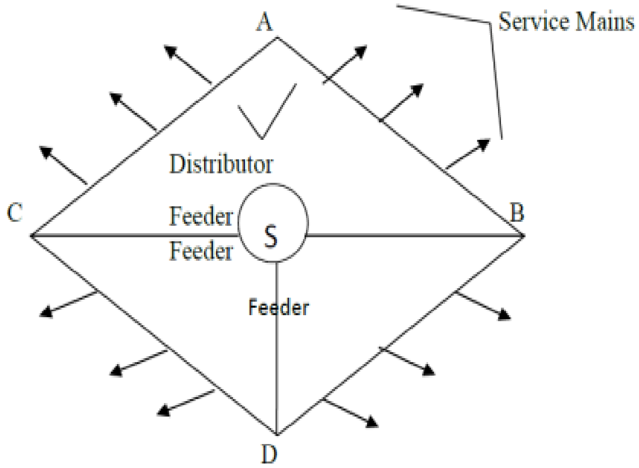

Figure 2.1: Single line diagram of a typical low tension distribution system (V K Mehta, 2006)

2.2.1. Classification of Distribution Systems

The electrical distribution system can be classified according to:

a) Nature of current

Due to the nature of the current, distribution system can be divided into two (i.e. A.C. and D.C. distribution system). A.C. distribution system is simple to build and more economical than the D.C. distribution system because converters are not necessary for the A.C. system. Generally, the A.C. distribution system can be divided into primary and secondary distribution systems.

Primary distribution system: is responsible for transmitting high voltage power from the substation to the distribution transformers, which then the voltage is stepped down into customer utilization levels. The voltage level in the primary distribution system typically ranges from 2.4 kV to 33 kV. It requires more expensive components and greater maintenance when compared to the secondary distribution system.

Secondary distribution: is responsible for delivering low voltage power from the distribution transformers to individual customers. The voltage level in the secondary distribution system typically ranges from 120 V to 240 V for residential customers and up to 400 V for commercial and industrial customers.

b) Construction type

According to the type of construction, the distribution system can be divided into an overhead or underground system. As we know, the underground system is more expensive than the corresponding overhead system. As a result, the underground system is typically used at places where an overhead system is impossible to build.

c) Connection Scheme

Due to the connection scheme, the distribution system can be divided into three; radial, ring main, and inter-connected distribution systems.

Radial distribution system: A radial system has a single path between the power sources and the consumers. It has only one power source for a group of customers. i.e. If there is a power outage, everyone in the group is left without electricity(Latreche & Bouchekara, 2020; V K Mehta, 2006).

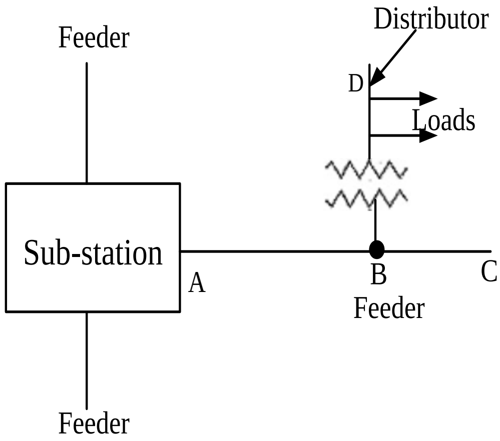

Figure 2.2: Radial distribution system

a) Advantages of a radial distribution system
    - It is simple in design and operation
    - It has a low initial cost
b) Disadvantages of a radial distribution system
    - Any fault on the feeder or distributor will cause power interruption for the entire group of customers. Because the consumers are dependent on a single feeder or distributor.
    - Due to load changes on the distributor, the end user would be subjected to serious voltage fluctuation.
    - The distributor nearest to the feeding point would be overloaded.

Ring Main distribution system: Each distributor is fed by two different feeders that radiate out from a single substation. A ring or loop system has two or more pathways between the power sources and the consumers.

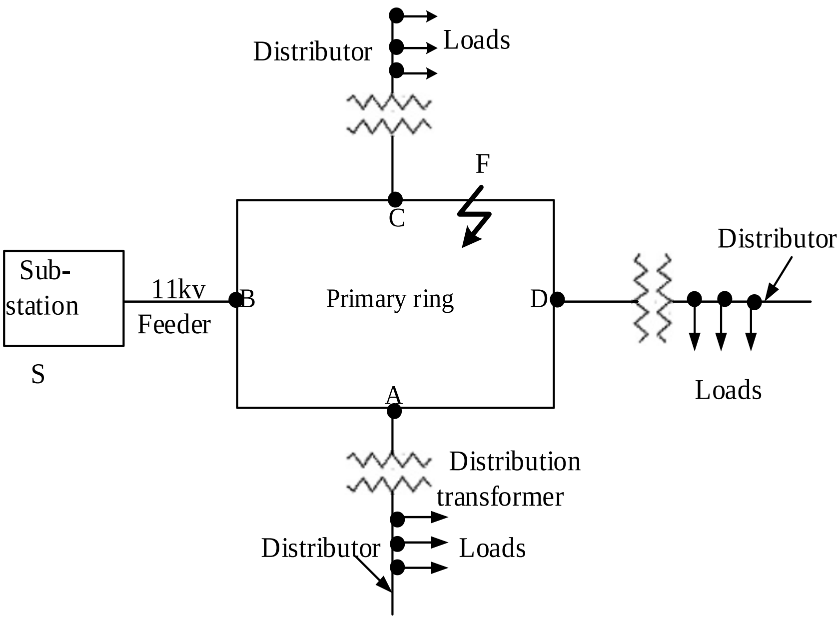

Figure 2.3: Ring main distribution system

a) Advantages of loop distribution system
- It has low voltage fluctuations at consumer terminals
- Even if there is a failure in any part of the feeder, the system is very reliable because each distributor is fed by two feeders.

b) Disadvantages of ring or loop distribution system
- It is more expensive than a radial distribution system as more conductors and switches are required.
- Difficult to design when compared to radial distribution system

Interconnected distribution system

When two or more substations are connected in a mesh/grid configuration, the system is called an interconnected distribution system. As shown in Figure 2.4, Substations S1 and S2 supply the closed feeder loop ABCD at locations D and C, respectiv ely. Distributors are connected to points E, F, G, and H of the feeder ring through distribution transformers (Gebru et al., 2021; V K Mehta, 2006).

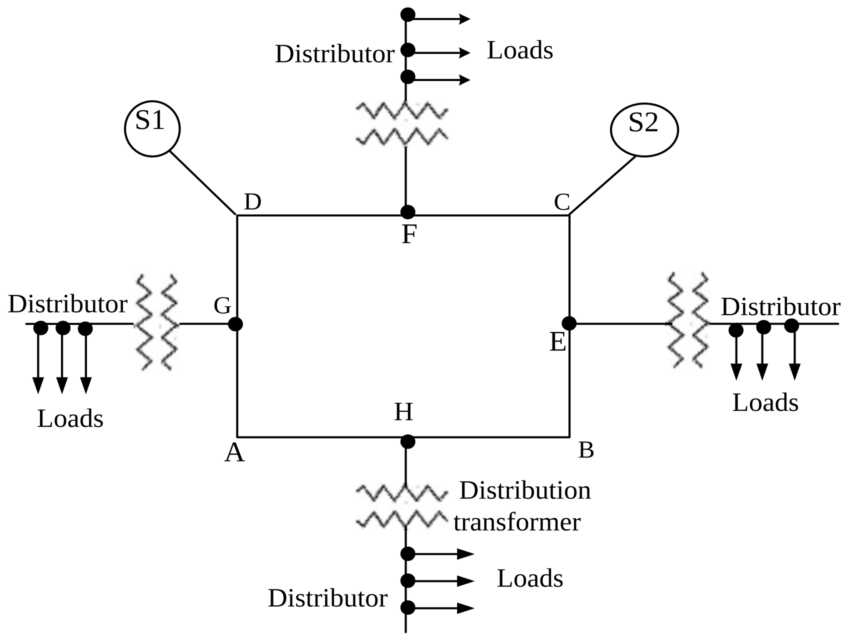

Figure 2.4: Interconnected distribution system

a) Advantages of an interconnected ring or loop distribution system

- It increases the service's reliability
- At peak load hours, any region serviced by the first generating station can be fed by the second generating station. This lowers the reserve power capacity and the system becomes more efficient.

b) Disadvantages of an interconnected distribution system

- It is more expensive than radial and loop distribution systems.
- It is difficult in designing, planning, and operation.

2.3. Power Loss and Voltage Drop Minimization Techniques for Distribution System

Losses in power system networks can be divided into technical and nontechnical losses. Technical losses are naturally occurring losses due to the material properties of the system's components. The heat produced in overhead power lines, distribution lines, transformer windings, and iron cores is the cause of these losses. Whereas, non-technical losses are caused by actions external to the power system, such as electricity theft brought on by unpaid electricity bills, billing errors, inaccurate meter readings, poor record-keeping, transformer overloading, and faulty meters, etc (Nyebuchi Amadi, 2020).

Power loss and voltage drop minimization techniques are essential for optimizing the performance and efficiency of electrical distribution systems(*Rudresh et al.*, 2012). Here are some common techniques used for this purpose:

i) **Reconductoring**: is the process of replacing the existing cable/conductor in the feeder with a large size (large cross-sectional area) to reduce the resistance. These methods give a large loss reduction; however, the cost of conductors and their installation is typically more than the cost of the energy saved. So, it is not used unless there is a special need.

ii) **Reconfiguration:** Network restructuring is simply changing the topology of a distribution network to reduce energy wastage and maximize the voltage profile. This can be achieved by opening or closing switches to change the power flow in the network. This method allows moving loads from heavy-loaded feeders to lightly loaded feeders and from higher resistance routes to lower resistance routes. The resistance route is the total resistance from the source to the load point. However, feeder reconfiguration is not economical for feeders that are unautomated and far apart.

iii) **Shunt Capacitors:** are connected near load points/receiving substations to increase feeder capacity, reactive power control, lower system loss, maximize the voltage profile of the feeder, and improve power factor. They are simple to use and less expensive than FACTS controllers, but they require protective equipment, have poor voltage control, and cause some disturbances.

iv) **Distribution Generation:** The integration of distributed generation sources, such as solar panels or wind turbines, into the distribution network, can help reduce power losses and voltage drops. Distributed generation refers to a small-scale energy production near the load center that adds active, reactive, or both types of energy to the distribution system. However, DG sources are relatively high costs, intermittent, and require proper protection to facilitate the transfer of power.

v) **Locating and Sizing of Distribution Transformer:** distribution transformers should be placed as close to the load as possible. This will reduce the amount of current flowing through the distribution lines, which will reduce power losses. In addition to this, large rating transformers should be replaced by smaller rating transformers that can effectively serve a smaller number of users.

   When a transformer is located at the end of a long distribution line, the current flowing through the line will be much higher than if the transformer were located closer to the load. This is because the resistance of the line will cause some of the voltage to be lost as heat, and the current will increase to compensate for the lost voltage.

vi) **Using Highly Voltage Distribution System:** High voltage distribution systems are used to reduce power losses by minimizing the current flow in the distribution network.

vii) **Reactive power compensation:** Reactive Power or VAR compensation is known as reactive power management to maximize an AC system's performance. The issue of reactive power compensation can be used for load and voltage support purposes. The objective is to obtain a corrected power factor and a true power balance with the load, and voltage support is mainly essential to minimize the voltage fluctuations of the transmission/distribution line. Generally, reactive power compensation is essential to maximize the voltage profile and minimize system losses when properly sized and positioned (Akram, 2018).

2.4. Flexible AC Transmission Systems (FACTS) Devices

FACTS controller is a power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability. FACTS technology has been applied for harmonic reduction, voltage stabilization, power quality improvement, demand control, power factor correction, loss minimization, voltage regulation, power flow control, and effective energy utilization (Ahmad & Sirjani, 2019; Press et al., n.d., 2000).

Classification of FACTS controllers

Due to the nature of connection in electrical power systems, FACTS controllers are categorized into four:

a) Shunt-connected controllers (SVC, STATCOM)
b) Series connected controllers (SSSC, TCSC, TSSC)
c) Combined series-series controllers (IPFC)
d) Combined shunt-series controllers(UPFC)

Based on the power electronics used in the controller, FACTS controllers are classified into:

- Variable impedance type
  - static VAr compensator (SVC)
  - thyristor-controlled series capacitor (TCSC)
- Voltage Source Converter (VSC) – based

- Satic compensator (STATCOM)
- Static synchronous series compensator (SSSC)
- Unified power flow controller (UPFC)
- Interline power flow controller (IPFC) (Padiyar, 2007) (Urinboy & Hasanov, 2021).

2.5. Distribution Flexible AC Transmission Systems (D-FACTS)

Distribution Flexible AC Transmission System (D-FACTS) devices are the most advanced power electronics-based devices used for power loss reduction, voltage stability, and power quality improvement.in distribution systems. These devices are designed to provide fast and accurate control of voltage and current to compensate for disturbances in the distribution system. Generally, D-FACTS devices have many advantages over FACTS devices such as low cost, compact size, and high performance(Akram, 2018). Distribution FACTS like dynamic voltage restorer (DVR), unified power quality conditioner (UPQC), and distribution static compensator (D-STATCOM).

a) **Distribution Static Synchronous Compensator (D-STATCOM)**: is a shunt-connected device that provides reactive power compensation by injecting or absorbing reactive power into the distribution system. It can also regulate the voltage at the point of connection by controlling the reactive power flow.
b) **Dynamic Voltage Restorer (DVR)**: is a series-connected device that injects voltage to compensate for voltage sags and swells in the distribution system.
c) **Unified Power Quality Conditioner (UPQC)**: It is the combination of series and shunt-connected devices that provide comprehensive compensation for both voltage and current in the distribution system. It can mitigate a range of power quality issues such as voltage sags/swells, harmonics, and unbalance.

Advantages of D-FACTS devices

- **Improved voltage stability**: D-FACTS devices can regulate the voltage at the point of connection and maintain it within acceptable limits. This can help to improve the stability of the distribution system and prevent system collapse.
- **Reduced power losses**: D-FACTS devices can help to reduce power losses in the distribution system by regulating the flow of reactive power and minimizing the occurrence of voltage sags and swells.

- **Improved power quality**: D-FACTS devices can mitigate a range of power quality issues such as voltage sags/swells, harmonics, and unbalance. This can help to improve the overall power quality of the distribution system.

Disadvantage of D-FACTS devices

- **High cost**: D-FACTS devices can be expensive to install and maintain, which can make them financially unfeasible for some applications.
- **Limited compensation range**: D-FACTS devices have a limited range of compensation, which may not be sufficient to address some power quality issues in the distribution system.
- **Complex control**: D-FACTS devices require complex control systems to ensure that they operate correctly and safely. This can make them difficult to integrate into existing distribution systems.

Table 2.1: Comparison of different D-FACTS devices

	DVR	D-STATCOM	UPQC
Advantages	▪ Fast response ▪ No harmonic distortion ▪ Independent control of voltage and current	▪ Fast response ▪ No harmonic distortion ▪ Independent control of voltage and current	▪ Comprehensive compensation ▪ Independent control of voltage and current
Dis Advantages	▪ Limited compensation range ▪ High cost	▪ Limited compensation range ▪ High cost	▪ Complex control ▪ High cost
Size	Large	Small	Large
Cost	High	High	High
Application	Voltage sag/swell compensation	Reactive power compensation	Voltage and current compensation

2.5.1. Distribution Static Compensator (D-STATCOM)

D-STATCOM is an important device used for reactive power compensation in electrical distribution networks. The device can inject or absorb reactive and active current at the point of common coupling (PCC). However, it is unable to inject active power for a long duration of time due to limited energy storage (Gowtham, 2015). D-STATCOM has several benefits over other D-FACTS devices, such as low harmonic production, low power losses, high control capability, small size, and low cost and this does not cause any operational problems such as resonance or harmonics. (Padiyar, 2007).

Main Components of D-STATCOM

D-STATCOM consists of the following main components:

a) **Coupling transformer:** A coupling transformer is used to connect the system voltage with the output voltage of the VSC through reactance. In addition to this, it provides isolation between the inverters in a multilevel inverter configuration to prevent the DC storage capacitor from being short-circuited with the inverter through switches.

b) **Voltage Source Converter (VSC):** is used to convert the DC voltage across storage devices into an AC output voltage at fundamental frequency.

c) **DC storage capacitor**: is used to provide constant DC voltage to the voltage source converter (VSC)(Mekhamer et al., 2020).

Operating Principle of D-STATCOM

Similarly to the operation of the synchronous machine, D-STATCOM supplies current at lagging and leading power factors for excited and overexcited respectively. The injected current by the D-STATCOM is $90°$ phase displacement with the system voltage. Due to this, there is no active power exchange between the system and VSC. However, the exchange of reactive power between the system and D-STATCOM can take place by changing the amplitude of the VSC output voltage. D-STATCOM has three modes of operation based on the amplitude of the system voltage and the VSC output voltage as shown in Figure 2.5.

i) **Capacitive mode:** When the magnitude of the system voltage (V_s) is less than the output voltage of the VSC (V_{vsc}), then D-STATCOM generates capacitive reactive power to the system.

ii) **Inductive mode:** When the magnitude of the system voltage (V_s) exceeds the output voltage of the VSC (V_{vsc}), D-STATCOM absorbs inductive reactive power from the system.

iii) **No load mode:** When the system voltage (V_s) and the output voltage of the VSC (V_{vsc}) have the same amplitude, there is no exchange of reactive power. In the event of very low voltage or power failure in the distribution system, there will be a true exchange of power with the AC system if the D-STATCOM obtains an external DC source for voltage management (S. M. S. Hussain & Subbaramiah, 2013).

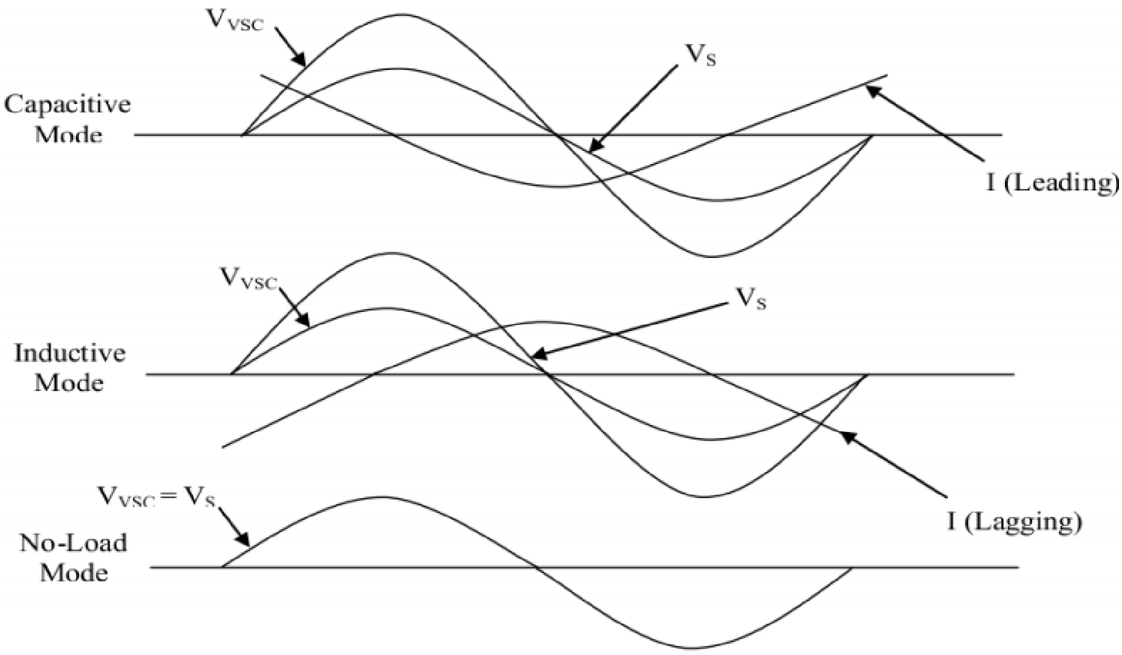

Figure 2.5: Operating Modes of D-STATCOM

Mathematical Modeling of D-STATCOM

A static model of a D-STATCOM is a mathematical model that describes the current and voltage relationships between the device and the distribution system under steady-state conditions. Let us consider a simple two-bus distribution system as shown in figure 2.6.

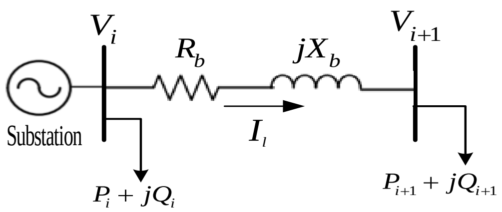

Figure 2.6: Single-line diagram of the bus distribution system (Arya & Loss, 2019).

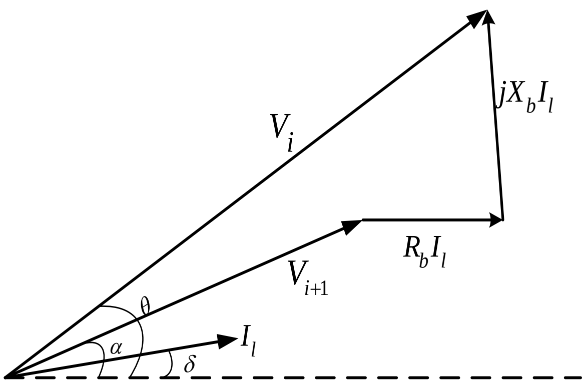

Figure 2.7: Phasor diagram for two bus distribution systems (Dash et al., 2022).

The relationship between the voltage and the current is given by:

$$V_{i+1}\angle\alpha = V_i\angle\theta - (R_b + jX_b)\times I_l\angle\delta \quad (2.1)$$

Where, $V_i\angle\alpha$ is the voltage at bus i

$V_{i+1}\angle\theta$ is the voltage at i+1

$R_b + jX_b$ is the branch/line impedance and $I_l\angle\delta$ is the branch/line current

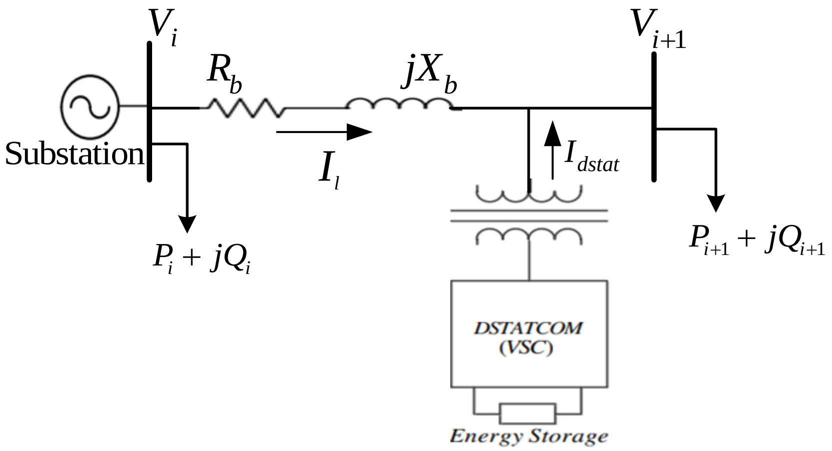

Figure 2.8: Single-line diagram of two bus systems with a DSTATCOM(Arya & Loss, 2019; Gupta & Kumar, 2018)

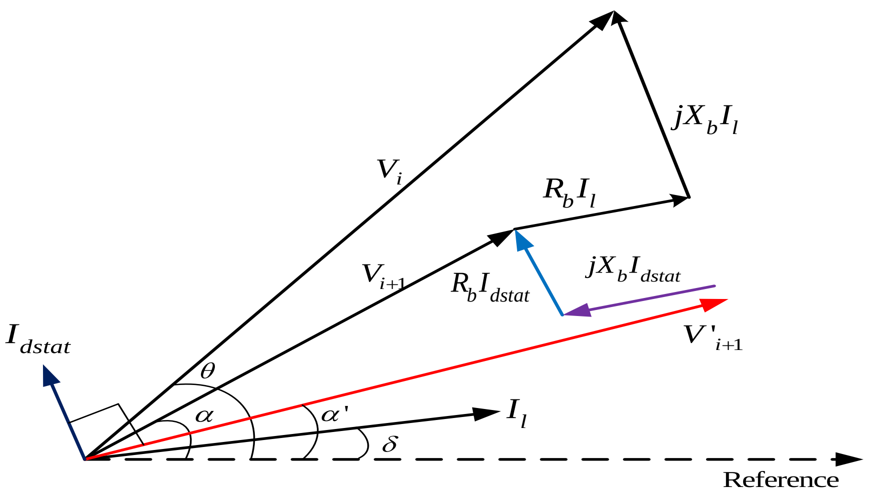

Figure 2.9: Phasor diagram for two bus distribution systems with D-STATCOM integration (Dash et al., 2022).

As shown in figure 2.8, the voltage at bus i+1 changes from $V_{i+1}\angle\alpha$ to $V'_{i+1}\angle\alpha'$ after D-STATCOM is integrated.

$$V'_{i+1}\angle\alpha' = V_i\angle\theta - (R_b + jX_b)\times(I_l\angle\delta + I_{dstat}\angle\alpha' + 90°) \quad (2.2)$$

Where, $V'_{i+1}\angle\alpha'$ is the voltage at bus i+1 after D-STATCOM is integrated

$V_i\angle\theta$ is the voltage at bus i

$R_b + jX_b$ is the branch/line impedance

$I_l\angle\delta$ is the branch/line current

$I_{dstat}\angle(\alpha'+90°)$ is the current injected by D-STATCOM

Separating the real and imaginary parts of equation (2.2) as follows:

$$V'_{i+1}\cos\alpha' = \mathrm{Re}(V_i\angle\alpha) - \mathrm{Re}(ZI\angle\delta) - RI_{dstat}\cos(\alpha'+90°) + XI_{dstat}\sin(\alpha'+90°) \quad (2.3)$$

$$V'_{i+1}\sin\alpha' = \mathrm{Im}(V_i\angle\alpha) - \mathrm{Im}(ZI\angle\delta) - RI_{dstat}\sin(\alpha'+90°) - XI_{dstat}\cos(\alpha'+90°) \quad (2.4)$$

Apply the following notations

$a = \mathrm{Re}(V_i\angle\alpha) - \mathrm{Re}(ZI\angle\delta)$, $b = \mathrm{Im}(V_i\angle\alpha) - \mathrm{Im}(ZI\angle\delta)$,

$h_1 = -R,\ h_2 = -X,\ C = V'_{i+1}$

$d = I_{dstat}$ *and* $x = \alpha'$

Substitute the above variables and constants into equation (2.3) and (2.4), we obtain

$$C\cos x = a - h_1 d\sin x - h_2 d\cos x \quad (2.5)$$

$$C\sin x = b + h_1 d\cos x - h_2 d\sin x \quad (2.6)$$

a, b, $h_1$and h_2 are constants, so we need to calculate d and x.

$$d = \frac{C\cos x - a}{-h_1\sin x - h_2\cos x} = \frac{C\sin x - b}{-h_2\sin x + h_1\cos x} \quad (2.7)$$

Suppose $y = \sin x$ and by equating the two terms we get:

$$\{(ah_2 - bh_1)^2 + (ah_1 - bh_2)^2\}y^2 + 2(ah_2 - bh_1)Ch_1 y + C^2h_1^2 - ah_1 + bh_2 = 0 \quad (2.8)$$

Assume $k_1 = ah_2 - bh_1$ *and* $k_2 = ah_1 - bh_2$, then equation (2.8) becomes:

$$(k_1^2 + k_2^2)y^2 + 2(k_1ch_1)y + (c^2h_1^2 - k_2^2) = 0 \quad (2.9)$$

By using the quadratic equation, we can determine the solution of variable y as shown below:

$$y = \frac{-2k_1Ch_1 \pm \sqrt{(2k_1Ch_1)^2 - 4(k_1^2 + k_2^2)(C^2h_1^2 - k_2^2)}}{2(k_1^2 + k_2^2)} \tag{2.10}$$

Therefore, the voltage phase angle can be calculated by:

$$\alpha' = x = \sin^{-1}(y) \tag{2.11}$$

Therefore, the injected reactive power, voltage, and current at bus i+1 is given as follows:

$$V'_{i+1} = |V'_{i+1}| \angle \alpha' \tag{2.12}$$

$$I_{dstat} = |I_{dstat}| \angle(\alpha' + \frac{\pi}{2}) = |I_{dstat}| \angle(\alpha' + 90°) \tag{2.13}$$

$$jQ_{dstat} = V'_{i+1} I^*_{dstat} \tag{2.14}$$

Where, $*$ denotes the conjugate of a complex variable(S. M. S. Hussain & Subbaramiah, 2013; Isha & Jagatheeswari, 2021).

2.6. Dragonfly Algorithm (DA)

One of the meta-heuristic optimization techniques which is proposed by Seyedali Mirjalili in 2015 G.C for solving single-objective, multi-objective, and discrete issues is known as the Dragonfly optimization algorithm. The dragonfly algorithm is inspired by the feeding and migratory phases of dragonflies found in nature. During the feeding phase, dragonflies are organized in small groups that cover a small area to hunt, moving back and forth with sudden changes in the flight path. In the dynamic phase, large groups of individuals form herds and migrate in one direction over long distances.

The above two swarming behaviors are very similar to the two primary meta-heuristic optimization phases (i.e. exploration and exploitation) (Hendardi et al., 2021; Mirjalili, 2016; Rahman et al., 2023). The primary goal of any swarm is to survive; therefore everyone should be drawn to food supplies and away from the outward enemy. In general, the swarm movements of the dragonfly depend on the following five main factors:

a) **Separation:** indicates avoiding collisions when they are in the same neighborhood. It can be calculated as follows::

$$S_i = -\sum_{j=1}^{N} P - P_j \tag{2.1}$$

Where, S_i is the i[th] dragonfly's separation motion

P is the individual's current position

P_j is the j[th] dragonfly's position in the neighborhood

N is the number of neighboring individuals

b) **Alignment**: shows the correlation of an individual's speed with other individuals in a neighborhood. The alignment is calculated by:

$$A_i = \frac{\sum_{j=1}^{N} V_j}{N} \tag{2.2}$$

Where, A_i represents the motion of alignment for i[th] dragonfly

V_j is the velocity of j[th] neighboring individual

c) **Cohesion**: is a habit of dragonflies that fly towards the center of search agents. It is given by:

$$C_i = \frac{\sum_{j=1}^{N} P_j}{N} - P \tag{2.3}$$

Where, C_i specifies the i[th] dragonfly's cohesion

P_j is the j[th] dragonfly's position in the neighborhood

P is the present individual

N is the neighborhood size

d) **Attraction towards a food source** is obtained by:

$$F_i = P^{+} - P \tag{2.4}$$

Where, P^{+} is the position of the food source

e) **Distraction outwards an enemy** can be determined as follows:

$$E_i = P^{-} + P \tag{2.5}$$

Where, P^{-} is the position of the enemy.

Both the step and position vector are taken into account to update the positions of artificial dragonflies in a search space and to reproduce their motions. The step vector is equivalent to the velocity vector in PSO, which indicates the direction of the movement of the dragonflies flying.

The step vector is given by:

$$\Delta P_{t+1} = (sS_i + aA_i + cC_i + fF_i + eE_i) + w\Delta P_t \tag{2.6}$$

Where s, a, c, f, and e represent the separation, alignment, cohesion, food, and enemy weight factor respectively; whereas w represents the inertia weight; ΔP_t and ΔP_{t+1} are the current and next step vectors respectively, and t is the current iteration.

The position vector can be determined as:

$$P_{t+1} = P_t + \Delta P_{t+1} \tag{2.7}$$

High alignment weight and low cohesion weight are assigned for the exploration phase, whereas low alignment weight and high cohesion weight are assigned for the exploitation phase.

Dragonflies should fly in a random walk search space when there is no neighboring solution, and the updated position vector can be calculated as follows:

$$P_{t+1} = P_t + Levy(d).P_t \tag{2.8}$$

Where, P_t and P_{t+1} are the current and next position vectors of dragonflies, d is the dimension of the position vectors and the Le´vy flight is determined by:

$$Levy(x) = 0.01 \times \frac{r_1 \times \sigma}{|r_2|^{\frac{1}{\beta}}} \tag{2.9}$$

Where r_1 and r_2 are random numbers in [0, 1] and β is a constant value of 1.5.

$$\sigma = \left(\frac{\Gamma(1+\beta) \times \sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right) \times \beta \times 2^{\left(\frac{\beta-1}{2}\right)}} \right)^{\frac{1}{\beta}} \tag{2.10}$$

Where $\Gamma(x) = (x-1)!$

2.6.1. Advantages of Dragonfly Algorithm

Dragonfly Algorithm (DA) is a relatively new swarm-based optimization algorithm that has many advantages and high performance over traditional optimization methods such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). Here are some of the advantages of DA over PSO and GA:

a) Efficient exploration of search space

Dragonfly Algorithm is more efficient than PSO and GA to explore the search space. This is because the Dragonfly Algorithm uses a more informed search strategy that allows it to focus its search on promising areas.

b) Adaptive search strategy

Another advantage of DA is its ability to adaptively modify its search strategy based on the fitness of the individuals in the swarm. This enables the algorithm to dynamically adjust its exploration and exploitation strategies to improve the quality of the solutions.

c) Better convergence speed

DA has been found to converge faster than PSO and GA for many optimization problems. This is due to its efficient search strategy and the ability to adaptively modify its search parameters to improve the convergence speed.

d) Robustness

DA is robust to changes in the problem environment and parameter settings. This is due to its adaptive search strategy, which enables it to adapt to changes in the problem environment and parameter settings.

2.6.2. Variants of the Dragonfly Algorithm

a) DA algorithm for single-objective problems

DA provides a solution set randomly to begin the optimization process. The step and position vectors of dragonflies are initialized to arbitrary values specified in the lower and upper bounds of the variables. Each iteration updates the step and position vectors of each dragonfly by using equation (2.6) and (2.7)/(2.8). For updating these two vectors, each dragonfly's region is chosen by calculating the Euclidean distance between all the dragonflies, and the position is updated iteratively until the final condition is met.

b) Binary Dragonfly Algorithm(BDA)

The positions of search agents cannot be changed by adding step vectors to position vectors since their position vectors can only be assigned by 0 or 1. So, the transfer function is used to change a continuous SI technique into a binary algorithm without changing the structure. The transfer function receives the velocity (step) values and produces a number between 0 and 1 that represents the likelihood of moving the individuals and updating their positions. The BDA algorithm uses the following transfer function to solve binary problems:

$$T(\Delta P) = \left| \frac{\Delta P}{\sqrt{\Delta P^2 + 1}} \right| \tag{2.9}$$

Eq.(2.9) is used to determine the probability of location change for all artificial dragonflies. The new updating position formula, which is shown in Eq.(2.10), is then used to update the position of search agents in binary search spaces.

$$P_{t+1} = \begin{cases} \neg P_t & r < T(\Delta P_{t+1}) \\ P_t & r \geq T(\Delta P_{t+1}) \end{cases} \quad (2.10)$$

Where, r is a number in [0, 1]

The BDA algorithm assumes all of the dragonflies as one swarm and simulates exploration/exploitation by modifying the swarming factors (i.e. s, a, c, f, e, and w).

c) Multi-objective Dragonfly Algorithm(MODA)

The MODA is a variant of the DA that can be used to solve multi-objective optimization problems. In multi-objective optimization problems, multiple objective functions need to be minimized or maximized simultaneously. The MODA works by first initializing a population of solutions. Each solution is represented as a vector of values, and each value represents the value of one of the objective functions. The algorithm then iteratively updates the solutions in the population, moving them towards better solutions. The update of a solution in the MODA is based on two factors: the distance to the best solution found so far, and the distance to the nearest reference point. The best solution is the solution that has the best values for all of the objective functions. The nearest reference point is a point that represents a compromise between the different objective functions.

CHAPTER THREE

METHODOLOGY AND SYSTEM MODELLING

3.1. Description of the Case Study Area

Debre Berhan town is located at latitude 9°40'46" N and longitude 39°31'57"E with 2830 m (9284 ft) elevation above sea level. It is in the Amhara region, North Shewa administrative zone, and district of Debre Berhan Zuria and is located 130 km away from Addis Ababa. The Debre Berhan Distribution system was started in 1969 G.C from mini hydropower of Abogedam which is found in the north of Veresa River and from a diesel source. Debre Berhan distribution substation receives 132KV power from the Legetafo Substation and supplies electric power to Debre Berhan town and the nearby areas. It has eight feeders and two step-down power transformers with ratings of 16MVA and 25MVA; both of the two transformers are used to step down 132KV to 33KV and 15KV for primary distribution. The first transformer feeds for two outgoing feeders; namely Dashen Beer and Ankober; and the second transformer feeds for six outgoing feeders; namely Habesha Beer, Rowrank, Aliyu Amba, Ankober, Debre Berhan Blanket factory, Mendida, and Sheno. Three of the total feeders provide electricity to Debre Berhan city and go to nearby small towns and villages, while the remaining four feeders provide electricity to different factories.

For this research, the Aliyu Amba feeder is selected, because this feeder travels a long distance, has high-frequency power interruption, and incorporates all kinds of loads.

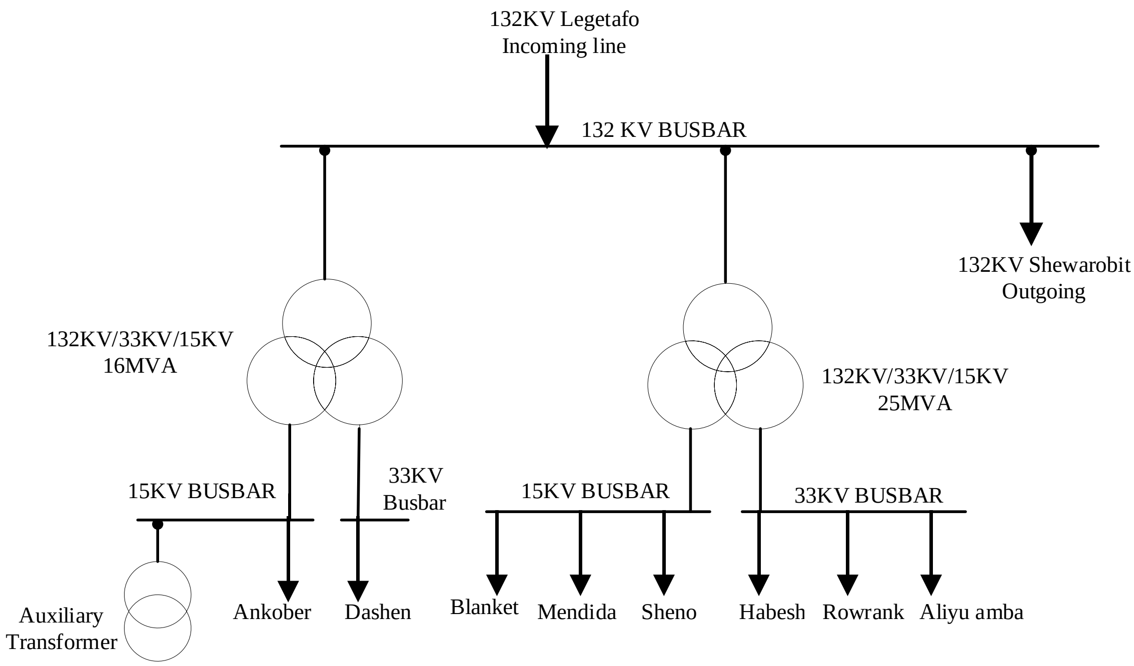

Figure 3.1: Single line diagram of Debre Berhan Distribution system

3.2. Data Collection

The important data required for this research work have been gathered from the Debre Berhan substation, Ethiopian Electric Utility (EEU), Debreberhan district, and Ethiopian Electric Power (EEP). The collected data includes the number of outgoing feeders, feeder length from the substation to end customers, monthly power interruption data of one year, the total number of distribution transformers, ratings of the power and distribution transformers, the conductor type and its impedance, and other important data's.

3.3. Single-Line Diagram Representation of Aliyu-amba Feeder

The radial configuration of the Aliyu-amba feeder consists of 193 buses, out of this node-1 is considered as a reference node, 140 nodes are connected to loads through step-down distribution transformers, and the remaining 52 are common coupling nodes. The single-line diagram of the Aliyu-amba distribution feeder is shown in Figure 3.1.

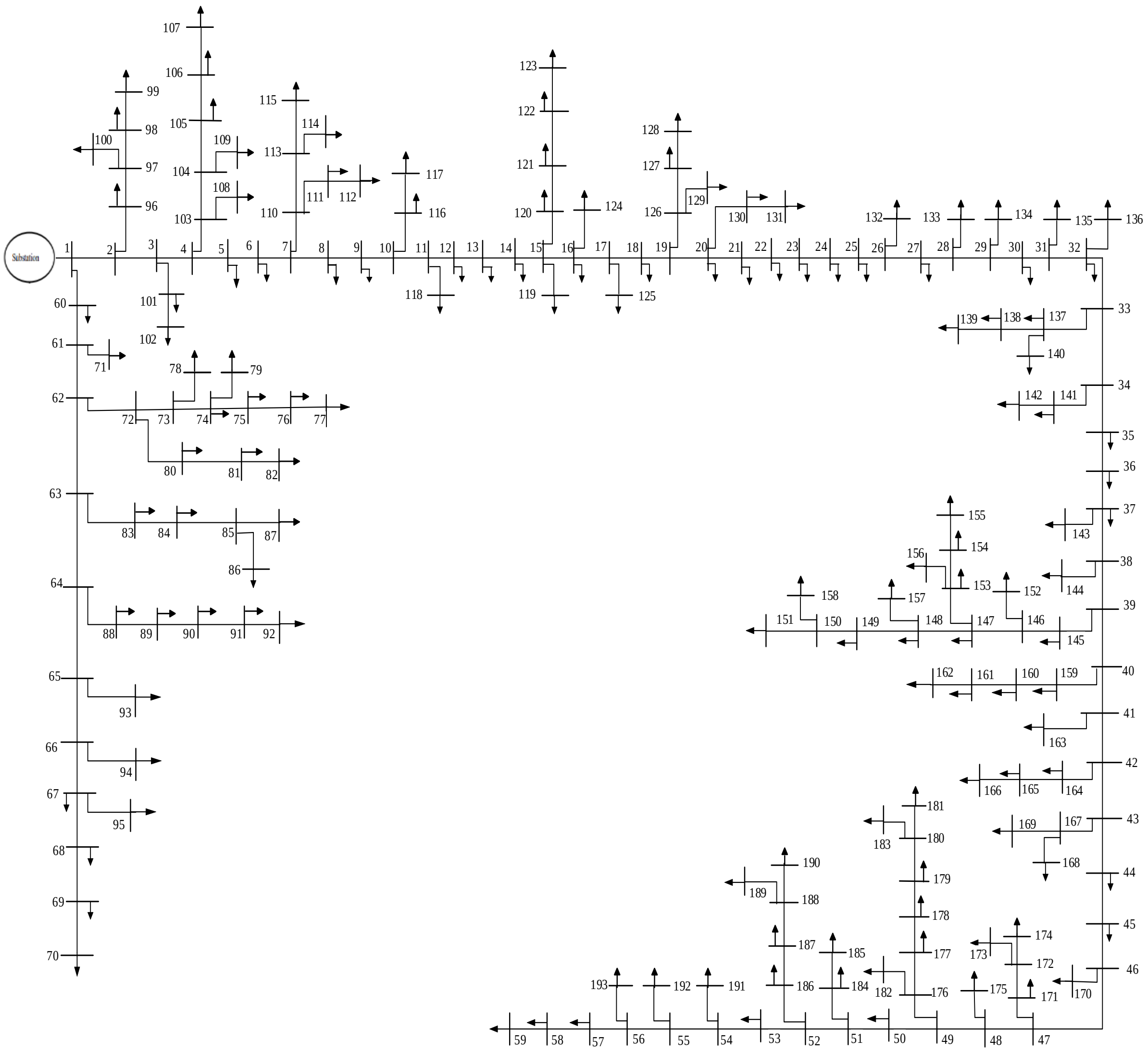

Figure 3.2: Single line diagram of Aliyu-amba distribution feeder

3.4. Impedance Calculation for Overhead Distribution Line

The overhead lines used in this feeder to distribute the medium voltage of 33 kV from the substation to the distribution transformer are all aluminum conductor types with sizes of AAC-50 and AAC-95 and the overall length of the feeder is 168.76 km. Both of these conductors have the same conductor arrangement as shown in figure 3.3.

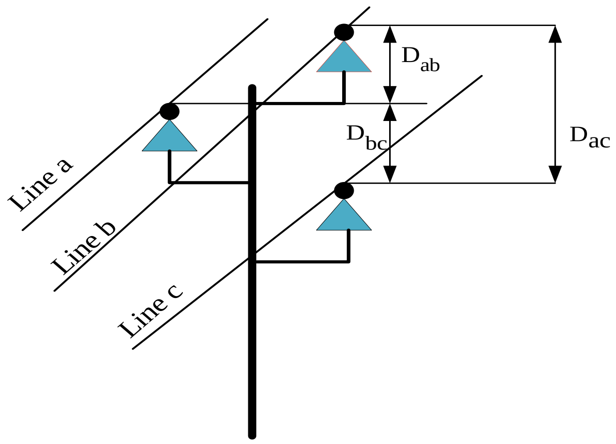

Figure 3.3: Overhead Conductor Arrangement of Aliyu-amba Feeder

The resistance and reactance values of the overhead lines will oppose the current flow and those are necessary for power loss, voltage drop, power flow, and short circuit analysis. The impedance of the conductors in a distribution system depends on the materials to be used, the size and configuration of the conductors, and the distances between them. The selected feeder uses stranded conductors of AAC-50 and AAC-95. The conductor manufacturers typically provide resistance per kilometer in tabular form for common frequencies (50 and 60 Hz), and such tables can be used to calculate resistance. However, the inductive reactance is calculated for a length of 1 kilometer and a frequency of 50 Hz. Finally, the positive sequence impedance of the conductors is determined by the following equations:

$$Z_a = R_a + j0.06283\ln\left(\frac{D}{GMR_a}\right)\Omega / km \quad (3.1)$$

$$D = \sqrt[3]{D_{ab} \times D_{bc} \times D_{ac}} \quad (3.2)$$

$$GMR_a = k \times r \quad (3.3)$$

Where, Z_a = impedance of conductor a in Ω*/km*

R_a = resistance of conductor a in Ω/km

D = distance between conductors in meter

D_{ab}, D_{bc}, and D_{ac} =distance between conductors a and b, b and c, and a and c

GMR_a = Geometric mean radius of conductor a

k = GMR factor

r = actual conductor radius

The overhead conductor parameters used in the Aliyu-Amba feeder are listed in Table 3.1, and the resistance factor of the conductors is taken from the standard overhead conductor data sheet shown in Appendix B.

Table 3.1: Overhead conductor parameters used in the feeder

Conductor type	Conductor size (mm^2)	Actual area (mm^2)	Stranding and wire diameter	Overall Diameter of a 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

Table 3.2: GMR Factor (k) and Strand Relationship for AAC conductor

Strands	GMR factor
7	0.7256
19	0.7577
37	0.7678
61	0.7722

Using equation (3.1), tables 3.1 and 3.2, the selected feeder's conductor impedance can be calculated as follows:

For AAC-50 $$Z_{50} = R_a + j0.06283\ln\left(\frac{D}{GMR_a}\right)\Omega / km$$

$$= 0.5785 + j0.06283\ln\left(\frac{\sqrt[3]{1.15\times0.64\times0.51}}{2.88\times10\wedge-3}\right)\Omega / km$$

$$= 0.5785 + j0.06283\ln\left(\frac{0.72135}{2.88\times10\wedge-3}\right)\Omega / km$$

$$= 0.5785 + j0.34703\ \Omega / km$$

For AAC-95 $$Z_{95} = R_a + j0.06283\ln\left(\frac{D}{GMR_a}\right)\Omega / km$$

$$= 0.3085 + j0.06283\ln\left(\frac{\sqrt[3]{1.15\times0.64\times0.51}}{4.129\times10\wedge-3}\right)\Omega / km$$

$$= 0.3085 + j0.06283\ln\left(\frac{0.72135}{4.129\times10\wedge-3}\right)\Omega / km$$

$$= 0.3085 + j0.3244\ \Omega / km$$

The positive sequence impedance of each line/branch is determined by multiplying the impedance per kilometer of the conductor by its length as shown in Appendix D. Since the line is short, we can neglect the shunt admittance of the overhead lines. Therefore, the line impedance is calculated as:

$$R_l = R_a \times L \text{ and } X_l = X_a \times L \tag{3.4}$$

Where; R_l is the line resistance

X_l is the line reactance

L is branch length in Km

R_a is the resistance of the conductor per km

X_a is the reactance of the conductor per km

3.5. Load Flow Analysis for Radial Distribution System

In the past few years, conventional power flow methods like Gauss-Seidel, Newton-Raphson, coupled and fast-decoupled have been widely used for power-system operation, control, and planning. However, these techniques are more suitable for transmission systems rather than distribution systems. This is due to the high R/X ratio, large number of buses and lines, and unbalanced loads connected in the distribution system. Due to these characteristics, conventional power flow techniques may produce poor convergence rates, require high computational time, and fail to meet the requirements of the distribution system. Therefore, to overcome the above problems the Forward/backward sweep power flow method is developed (Kawambwa et al., 2021). In this research work, the Forward/backward sweep-based power flow method is applied.

Backward/Forward sweep power flow

The backward/forward sweep is very effective for power distribution systems, but it requires renumbering of the nodes or branches when used for tasks involving networks with dynamic topology structures. This method consists of two steps: the backward sweep and the forward sweep (Gebru et al., 2021; Rana et al., 2014).

i. Backward load flow method

Considering the ith bus of a distribution network, the load current at bus i is calculated as follows:

$$I_L(i) = \left(\frac{S_L(i)}{V(i)}\right)^* = \left(\frac{P_L(i) + jQ_L(i)}{V(i)}\right)^* = \left(\frac{P_L(i) - jQ_L(i)}{V(i)^*}\right) \tag{3.5}$$

$$for\ i = 1,2,3,............,n$$

Where, $I_L(i)$ is the load current at bus i

$S_{L(i)}$ is the apparent power at each node

$V(i)$ the voltage at bus i

$P_L(i)$ and $Q_L(i)$ are the active and reactive power demands at bus i respectively

N is the total number of buses

In the backward sweep, the line (branch) currents are calculated by applying Kirchhoff's current law (KCL) to the distribution network starting from the farthest node to the source node of the feeder(Alam et al., 2018).

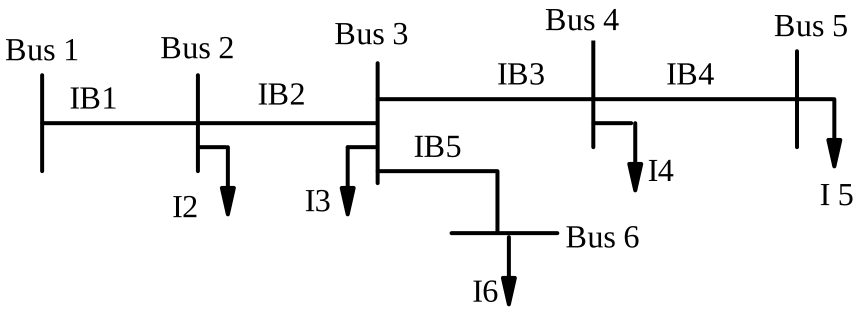

Figure 3.4: Simplified 6-bus radial distribution system

For the distribution network shown in Figure 3.3, each branch current is calculated as follows:

$$\begin{aligned} I_{B1} &= I_{L2} + I_{L3} + I_{L4} + I_{L5} + I_{L6} \\ I_{B2} &= I_{L3} + I_{L4} + I_{L5} + I_{L6} \\ I_{B3} &= I_{L4} + I_{L5} \\ I_{B4} &= I_{L5} \\ I_{B5} &= I_{L6} \end{aligned} \tag{3.6}$$

Equations (3.6) can be expressed in a matrix form as follows:

$$\begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_{L2} \\ I_{L3} \\ I_{L4} \\ I_{L5} \\ I_{L6} \end{bmatrix} \tag{3.7}$$

The above matrix can be written in a simplified form as:

$$[I_B] = [BIBC][I_L] \tag{3.8}$$

Where BIBC is the bus injection to branch current matrix and contains values of 0 and 1.

ii. **Forward load flow method**

In the forward sweep, node voltages are computed using KVL starting from the source node to the farthest node of the feeder and laterals.

For the distribution network shown in Figure 3.3, the node voltages are determined by:

$$\begin{aligned} V_2 &= V_1 - I_{B1}Z_{12} \\ V_3 &= V_2 - I_{B2}Z_{23} = V_1 - I_{B1}Z_{12} - I_{B2}Z_{23} \\ V_4 &= V_3 - I_{B3}Z_{34} = V_1 - I_{B1}Z_{12} - I_{B2}Z_{23} - I_{B3}Z_{34} \\ V_5 &= V_4 - I_{B5}Z_{45} = V_1 - I_{B1}Z_{12} - I_{B2}Z_{23} - I_{B3}Z_{34} - I_{B5}Z_{45} \\ V_6 &= V_3 - I_{B5}Z_{56} = V_1 - I_{B1}Z_{12} - I_{B2}Z_{23} - I_{B5}Z_{56} \end{aligned} \tag{3.9}$$

The above equations can be rewritten in a matrix form as follows:

$$\begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \end{bmatrix} \tag{3.10}$$

BCBV is the branch current to bus voltage which is given by:

$$[BCBV] = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \tag{3.11}$$

$$[BCBV] = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \tag{3.12}$$

$$[BCBV] = [BIBC]^T [Z_D] \tag{3.13}$$

Equation 3.10 can be rewritten as:

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & Z_{56} \end{bmatrix} \begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \end{bmatrix} \tag{3.14}$$

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} I_{B1} \\ I_{B2} \\ I_{B3} \\ I_{B4} \\ I_{B5} \end{bmatrix} \tag{3.15}$$

$$\Delta V = [BCBV][I_B] = [BIBC]^T [Z_D][I_B] \tag{3.16}$$

According to equation (3.18) the bus voltage at the (k+1)th iteration has the following generic form:

$$\left[V^{k+1}\right] = [V_1] - [BCBV][I_B] \tag{3.17}$$

By substituting equation (3.8) into equation (3.16), we get

$$\Delta V = [BCBV][BIBC][I_L] \tag{3.18}$$

$$\Delta V = [BIBC]^T [Z_D][BIBC][I_L] \tag{3.19}$$

The distribution load flow matrix (DLF) is formulated as follows:

$$[DLF] = [BCBV][BIBC] = [BIBC]^T [Z_D][BIBC] \tag{3.20}$$

Substitute equation (3.20) into equation (3.19)

$$\Delta V = [DLF][I_L] \tag{3.21}$$

The iterative solution for the distribution system load flow can be obtained as:

$$\left[\Delta V^{k+1}\right] = [DLF]\left[I_L{}^k\right] \tag{3.22}$$

$$\left[V^{k+1}\right] = [V_1] + \left[\Delta V^{k+1}\right] \tag{3.23}$$

iii. Power Loss Calculation

The per phase total active and reactive power losses of branch j can be calculated as follows:

$$P_{loss}(i,i+1) = |I^2(i)| \times R(i,i+1) \tag{3.24}$$

$$Q_{loss}(i,i+1) = |I^2(i)| \times X(i,i+1) \tag{3.25}$$

Where, $P_{loss}(i,i+1)$ is the active power loss of the line between bus i and i+1

$Q_{loss}(i,i+1)$ is the total reactive power loss of the line between bus i and i+1

$I(i)$ is the branch current flowing from bus i to bus i+1

$R(i,i+1)$ is the resistance of the line between bus i and i+1

$X(i,i+1)$ is the reactance of the line between bus i and i+1

N_{br} is the total number of branches

The total active power loss and reactive power loss of the system can be determined as follows:

$$P_{loss} = \sum_{i=1}^{N_{br}} P_{loss}(i, i+1) \tag{3.26}$$

$$Q_{loss} = \sum_{i=1}^{N_{br}} Q_{loss}(i, i+1) \tag{3.27}$$

iv. Voltage drop calculation

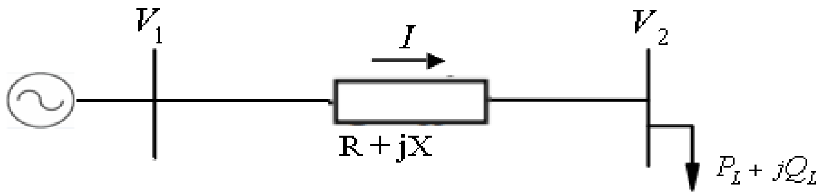

Figure 3.5: Single-line diagram of the two-bus radial distribution system (Salkuti, 2021).

Consider two bus distribution systems as shown in Figure 3.4. The current supplied to the load (I) can be calculated as:

$$I = \left(\frac{S}{V_2}\right)^* = \left(\frac{P_L - jQ_L}{V^*{}_2}\right) \tag{3.28}$$

The voltage drop due to the distribution line can be calculated as:

$$\begin{aligned} V_1 - V_2 &= I\left(R + iX\right) \\ &= \left(\frac{P_L - jQ_L}{V^*{}_2}\right)\left(R + jX\right) \\ &= \frac{\left(P_L R + XQ_L\right) - j\left(XP_L - RQ_L\right)}{V_2} \end{aligned} \tag{3.29}$$

Where, V_1 and V_2 are sending and receiving end voltages respectively

P_L and Q_L are the real and reactive power demands respectively

- The following are the proposed load flow solution algorithm procedures:

Step1: Read line data and bus data of the system

Step 2: Initialize all bus voltages as 1.0 p. $\angle 0^\circ$

Step 3: Set an iteration i.e. $k = k+1,\ k = 0,1,2,\ldots\ldots\ldots \max iter$

Step 4: Compute the load current at each bus of the system using equation (3.5)

Step 5: Formulate the Bus Injected to Branch Current (BIBC) matrix

Step 6: Compute the current flow at each branch of the network using equation (3.8)

Step 7: Formulate BCBV matrix using equation (3.13)

Step 8: Calculate the DLF matrix using equation (3.20)

Step 9: Update the voltage at each bus of the network using equation (3.22) and (3.23)

Step 10: Compute the power loss of each branch using equations (3.10) and (3.11).

3.6. Problem Formulation

a) Objective function: For this study, the objective function includes minimizing both active and reactive power loss and voltage profile improvement.

- Power loss minimization

The total active power loss of the distribution system is calculated by:

$$f_1 = \sum_{i=1}^{N_{br}} I_i^2 \times R_i \tag{3.30}$$

The total reactive power loss of the distribution network is given by:

$$f_2 = \sum_{i=1}^{N_{br}} I_i^2 \times X_i \tag{3.31}$$

Where I_i is the branch current; X_i and R_i are the resistance and reactance values of the ith branch respectively, and N_{br} is the total system branches.

- The total power loss reduction percentage is calculated as follows:

$$\%\text{Active power loss reduction} = \frac{P_{L(Base)} - P_{L(DSTAT)}}{P_{L(Base)}} \times 100 \tag{3.32}$$

$$\%\text{Reactive power loss reduction} = \frac{Q_{L(Base)} - Q_{L(DSTAT)}}{Q_{L(Base)}} \times 100 \tag{3.33}$$

- Minimize voltage deviation

$$f_3 = \sum_{i=1}^{N_{bus}} (1 - V_i)^2 \tag{3.34}$$

Where f_3 is the third objective function; V_i is the voltage of the ith bus and N_{bus} is the total number of buses.

The general multi-objective function is formulated using the weight sum method as shown in equation (3.35):

$$Minimize(MOF) = Min(w_1 \times f_1 + w_2 \times f_2 + w_3 \times f_3) \tag{3.35}$$

$$w_1 + w_2 + w_3 = 1 \tag{3.36}$$

b) System constraints: consists of equality and inequality constraints

- **Equality constraints**: represent the active and reactive power flow equations in the radial distribution system.

$$P_S = \sum_{i=1}^{N_{br}} P_D + \sum_{i=1}^{N_{br}} P_L \quad (3.37)$$

$$Q_S + Q_{DSTAT} = \sum_{i=1}^{N_{br}} Q_D + \sum_{i=1}^{N_{br}} Q_L \quad (3.38)$$

- **Inequality constraints**: The inequality constraint includes bus voltage, D-STATCOM size, and line thermal limits.

i) Bus voltage limit: The voltage at each bus must remain within the acceptable/permissible range.

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (3.39)$$

Where, V^{min} and V^{max} are the minimum and maximum bus voltage limits in the i^th bus respectively, with V^{min} = 0.95p.u and V^{max} = 1.05p.u.

ii) Line thermal limit: the current passing through each branch must be within the maximum current carrying capacity of the conductor:

$$I_i \le I_i^{\max} \quad (3.40)$$

$$for\ i = 1, 2, 3, ... N_{br}$$

Where N_{br} is the total number of branches in the system.

iii) D-STATCOM size limit: The total reactive power injected by D-STATCOM (Q_{DSTAT}) is not to exceed the total reactive power demand (Q_{D}) in the distribution system.

$$Q^{\min}_{DSTAT} \le Q_{DSTAT} \le Q^{\max}_{DSTAT} \quad (3.41)$$

3.7. Implementation of Dragonfly Algorithm

The Dragonfly Algorithm is a nature-inspired optimization algorithm that is based on the behavior of dragonflies. The algorithm is particularly effective for solving complex and multimodal optimization problems.

Here are the steps for implementation of the Dragonfly Algorithm:

1. *Initialize the population*: Generate an initial population of dragonflies randomly within the search space. Each dragonfly represents a potential solution to the optimization problem.

2. *Set algorithm parameters*: set the maximum number of iterations, specify the number of dragonflies in the population, and determine the ranges and constraints of the search space.

3. *Evaluate the fitness*: Evaluate the fitness of each dragonfly in the population. The fitness value indicates how good a particular dragonfly's solution is in solving the optimization problem.

4. *Update the position of the dragonflies*: Each dragonfly adjusts its position by considering the positions and fitness values of other dragonflies in its vicinity. During the movement, attractant forces bring dragonflies closer to better solutions, while repellent forces push them away from worse solutions. The movement is also influenced by randomization to explore new areas of the search space.

5. *Evaluate the fitness for the updated position*

6. *Update the global best solution*: Replace the current best solution with the updated values if a better solution is found. Otherwise, go back to step 4

7. *Stop criteria:* If the maximum number of iterations is reached then print the results.

- The following are the proposed load flow solution algorithm procedures:

Step 1: Read line data and bus data of the system

Step 2: Perform base case power flow analysis using the BFS load flow method to compute each bus voltage and each branch power loss.

Step 3: Set algorithm parameters like population size, maximum iteration, lower and upper bounds, and number of D-STATCOM.

Step 4: Set iteration counter k = 1.

Step 4: Evaluate the fitness function of each dragonfly, and then select the individual best (pbest).

Step 5: Update the step and position of the dragonflies using equations (2.7) and (2.8).

Step 6: Evaluate the fitness function for the updated position and compare Pbest and Gbest with the previous.

Step 7: Repeat until maximum iteration reached

Step 8: Return Gbest at the optimal solution

Step 9: Perform final load flow analysis by returning Gbest at optimal solution i.e. optimal size and location of D-STATCOM.

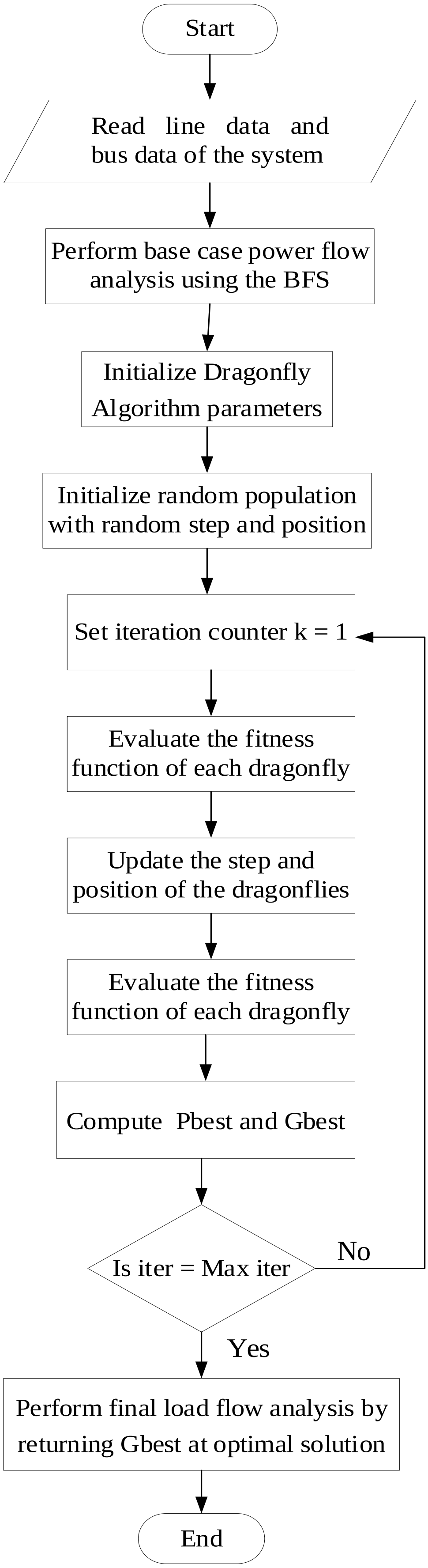

Figure 3.6: Flow Chart for Power Flow with D-STATCOM

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter deals with the simulation results and their analysis. The proposed system was tested on a 193-bus Aliyu-amba Feeder in the Debre Berhan distribution system. The simulation of the results was carried out in MATLAB R2018, and the power flow analysis was performed using the forward/backward sweep load flow method. Load flow analysis has an important role during the study of power loss and voltage drop calculations and cost analysis of the distribution feeders. The test system has 193 buses, 192 branches, 33 KV nominal voltage, and a total system load of 9.024 MW and 6.768 MVAR.

4.1. Weight Factor Selection

When optimizing power systems, weight factors play an important role in determining the relative importance of different objectives in the objective function. These factors are typically positive values that sum up to 1, reflecting the relative importance of the objectives. The weight factors are incorporated into the optimization process through a fitness function, which combines the objective functions (active and reactive power loss reduction and voltage profile improvement) with the assigned weight factors. The fitness function evaluates the quality of a solution based on these objectives and weight factors and it is formulated by equation (3.35). By adjusting the weight factors, system operators can influence the trade-off between power loss reduction and voltage profile improvement, allowing them to find a balance that aligns with their specific goals and requirements. Power loss reduction is given more attention in this study because it lowers operating costs overall significantly. This does not mean the other two factors are not significant. As shown in Table 4.1, the chosen weights were $w1 = 0.5$ for reducing real power loss, $w2 = 0.4$ for reducing reactive power, and $w3 = 0.1$ for enhancing the voltage profile.

Table 4.1: Effects of Weights on Best Fitness

$w1$	$w2$	$w3$	Best Fitness
0.8	0.1	0.1	0.2625
0.7	0.2	0.1	0.2621
0.7	0.1	0.2	0.5146
0.6	0.3	0.1	0.2617

0.6	0.2	0.2	0.5142
0.6	0.1	0.3	0.7667
0.5	**0.4**	**0.1**	**0.2613**
0.5	0.3	0.2	0.5138
0.5	0.2	0.3	0.7663
0.5	0.1	0.4	1.0168

4.2. Case-1: Base Case (System without D-STATCOM)

Based on the collected data given in Appendix D and E, the base case power losses and voltage profile of the selected feeder were computed using the backward-forward load flow method, and the corresponding results are listed in Table 4.2. The voltage profile of 130 buses, out of 193 total buses is below the acceptable minimum voltage limit (i.e. 0.95p.u.) and the minimum bus voltage is 0.84022p.u at bus number 59. The base case voltage profile of each bus is shown in figure 4.1. The feeder's voltage profile can be affected by the load on the line and the distance traveled. As we know, the longer the feeder length, the worse the voltages drop. The total real and reactive power losses of the given system under the base case are 1079.779 KW and 693.5628 KVAR respectively. The power loss for each branch is shown in Figure 4.2.

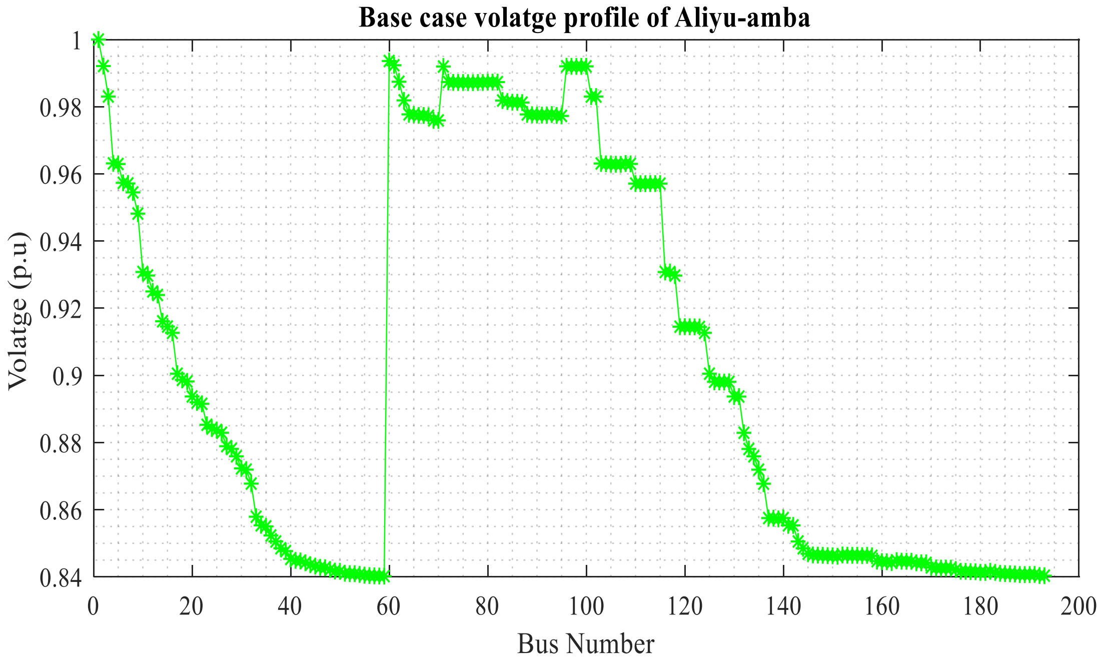

Figure 4.1: Base case voltage profile of Aliyu-amba Feeder

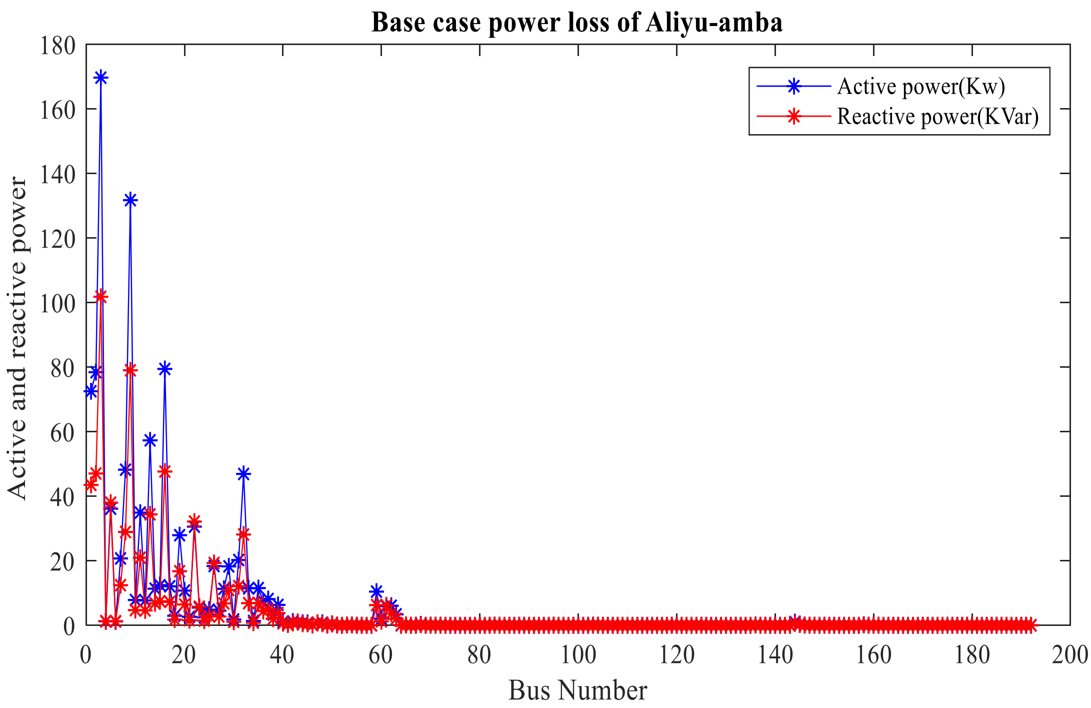

Figure 4.2: Base case active and reactive power losses of Aliyu-amba Feeder

4.3. Case-2: System with D-STATCOM

In this case, the Dragonfly optimization technique has been used to determine both the optimal size and location of D-STATCOM. The optimum placement of D-STATCOM to minimize the multi-objective function was obtained at buses 39 and 50 where two D-STATCOMs with an equal capacity of 2707 KVAR are integrated with the existing distribution system. In this instance, the overall active power loss decreases from 1079.779 KW to 583.984 KW, and the reactive power loss also decreased from 693.5628 KVAR to 377.1519 KVAR. However, When one D-STATCOM with 5414 KVAR capacity is connected with the distribution system (i.e. at bus 43), the total active power loss is decreased from 1079.779 KW to 598.8804 kW, and the reactive power loss also decreases from 693.5628 KVAR to 385.1634 KVAR. After the integration of one or two D-STATCOMs in the distribution system, the voltage profile of all the buses became within the acceptable range i.e. between 0.95p.u and 1.05pu, and the voltage profile of bus 59 has improved from 0.84022p.u to 0.9541p.u. Based on the result of this study, the integration of two D-STATCOMs gave better results than the integration of one D-STATCOM. Therefore, the voltage profile of each bus and the losses of each branch are shown in the figures below.

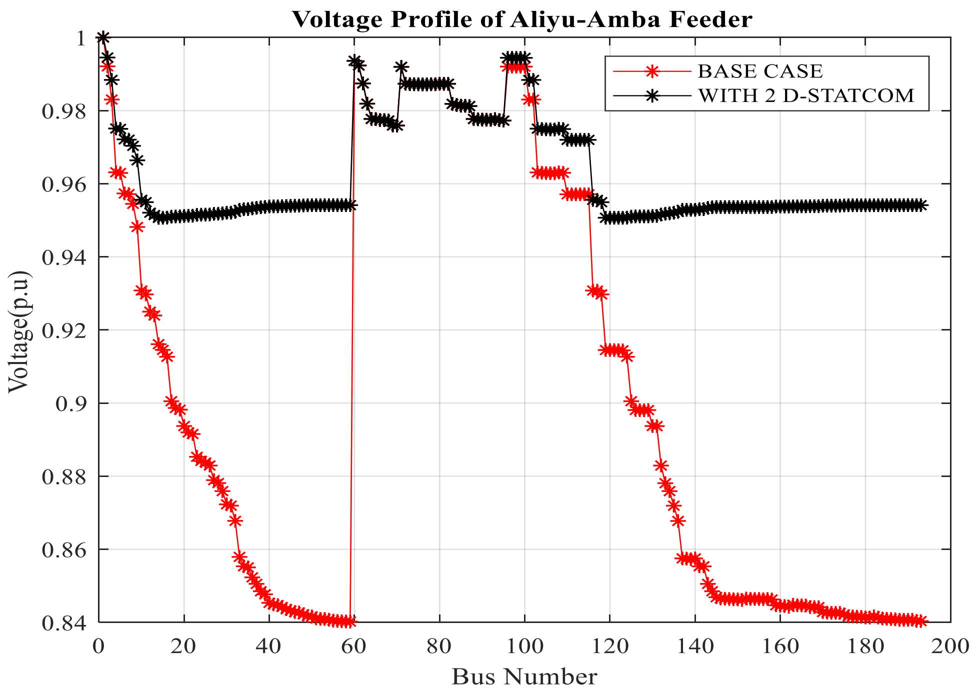

Figure 4.3: Voltage profile of Aliyu-amba Feeder before and after integration of D-STATCOM

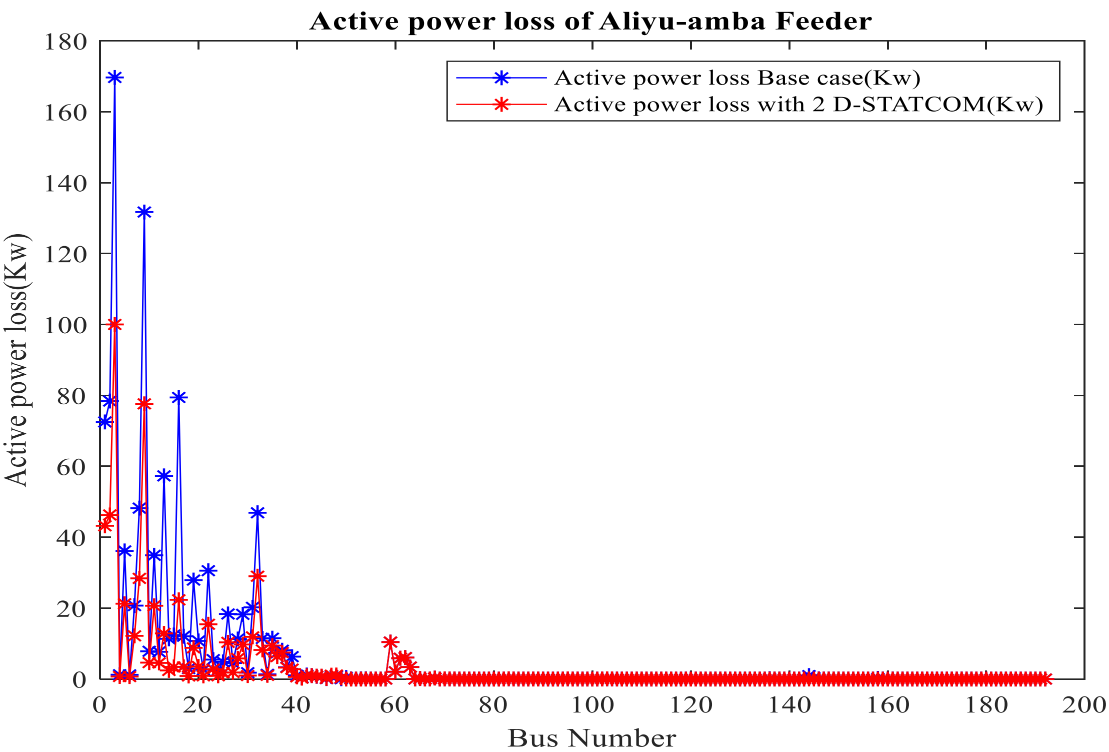

Figure 4.4: Active power losses in each branch of Aliyu-amba Feeder before and after integration of D-STATCOM

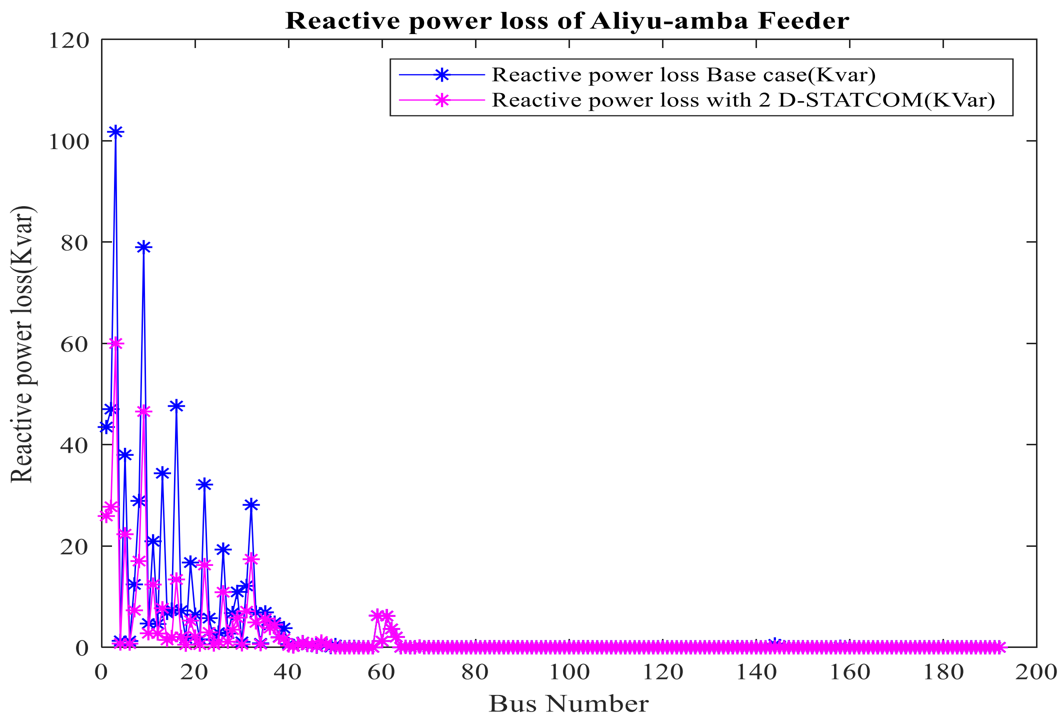

Figure 4.5: Reactive power losses in each branch of Aliyu-amba Feeder before and after integration of D-STATCOM

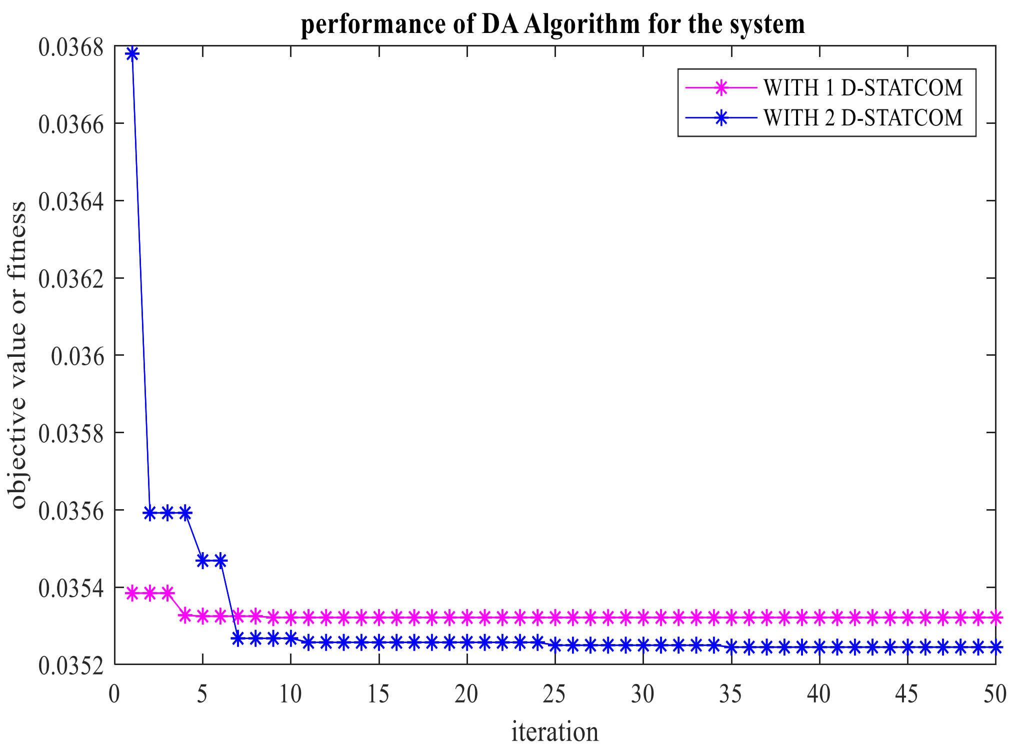

Figure 4.6: Convergence curve of DA with one and two D-STATCOMS

Table 4.2: Result summary of all cases

No	Parameter	Case-1	Case-2
1	Minimum bus voltage (p.u.)	0.84022 @ bus 59	0.95066 @ bus 14
2	Active power loss (KW)	1079.779	583.984
3	Reactive power loss (KVAR)	693.5628	377.1519
4	Maximum voltage deviation (%)	15.978	4.9341
5	Active power loss reduction (%)		45.916
6	Reactive power loss reduction (%)		45.621
7	Size of D-STATCOM (KVAR)		2707, 2707
8	Location of D-STATCOM (Bus No)		39, 50

4.4. Cost Analysis

After finding the best solution to the problem, cost analysis is crucial for evaluating the economic viability of the devices. The cost analysis for this research work includes energy loss cost, total cost of D-STATCOM, and total cost savings.

i) Cost of energy loss (CEL)

The cost of energy loss of the selected feeder is determined by:

$$CEL = Energy\ loss \times E_C \quad (4.1)$$

Where CEL is the cost of energy loss

E_C is the energy cost rate (Birr/kwh)

T is time (h)

a) The annual cost of energy loss before the integration of D-STATCOM is calculated as follows:

$$\begin{aligned} Annual\ energy\ loss &= P_{Loss} \times T \\ &= 1079.779\ KW \times 8760h \\ &= 9,458,864.04\ KWh \end{aligned} \quad (4.2)$$

Based on the revised EEU tariff, the tariff is 1.6787 Birr/Kwh as shown in Appendix C. So, the annual cost of energy loss can be determined by using equation (4.3):

$$\begin{aligned} Annual\ Cost\ of\ Energy\ Loss &= Annual\ Energy\ loss \times E_C \\ &= 9,458,864.04\ KWh \times 1.6787\ Birr / KWh \\ &= 15,878,565.064\ ETB \end{aligned} \quad (4.3)$$

b) The annual cost of energy loss after integration of D-STATCOM

$$Annual\ energy\ loss = P_{Loss} \times T$$
$$= 583.984\ KW \times 8760\ h \qquad (4.4)$$
$$= 5{,}115{,}699.84\ KWh$$

$$Annual\ Cost\ of\ Energy\ Loss = Annual\ Energy\ loss \times E_C$$
$$= 5{,}115{,}699.84\ KWh \times 1.6787\ Birr / KWh \qquad (4.5)$$
$$= 8{,}587{,}725.32\ ETB$$

ii) Net profit

Due to the integration of D-STATCOM, the overall real power loss of the system has been reduced to 583.984 KW from 1079.779 KW. As a result, the annual cost of energy loss also reduces from 15,878,565.064 Birr to 8,587,725.32 Birr. Therefore, the net profit (cost of saving) is the difference between the cost of energy loss in the base case and the cost of energy loss after the integration of D-STATCOM as shown in equation (4.6).

$$Net\ profit = \begin{pmatrix} Cost\ of\ energy\ loss \\ before\ integration \end{pmatrix} - \begin{pmatrix} Cost\ of\ energy\ loss \\ after\ integration \end{pmatrix}$$
$$= 15{,}878{,}565.064 - 8{,}587{,}725.32 \qquad (4.6)$$
$$= 7{,}099{,}839.743\ \text{Birr}$$

iii) Total cost of D-STATCOM

The cost of a D-STATCOM per KVAR is 50 US$ (Gupta & Kumar, 2018). In this study, the optimized D-STATCOM size is 5414 KVAR; and based on Commercial Bank of Ethiopia exchange rates on September 10, 2023, 1 USD = 55.21 ETB. The total cost of D-STATCOM is 14,945,347 Birr and the installation cost is 480,000 Birr.

iv) Payback period calculation

The payback in a year is calculated by the following equation (4.7).

$$Payback\ period = \frac{investment\ cost}{annual\ net\ profit}$$
$$= \frac{14{,}945{,}347\text{Birr} + 480{,}000\text{Birr}}{7{,}099{,}839.743\text{Birr}} \qquad (4.7)$$
$$= 2.17\ \text{years}$$

The cost of analysis indicates that the payback period for the initial investment cost is 2.17 years.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1. Conclusion

In this study, the Dragonfly algorithm was used to determine the optimal size and location of the D-STATCOM to minimize power loss and improve the voltage profile. The algorithm considers various system parameters, constraints, and objectives to find the optimal solution. By injecting reactive power and providing voltage support at strategic locations, the D-STATCOM responds to power demand, reducing voltage drops and reducing resistance losses. This leads to improved system efficiency and reduced energy wastage. The backward-forward power flow approach was used to analyze the load flow for the selected distribution feeder both before and after D-STATCOM integration.

From the base case simulation results, the total active and reactive power losses were observed to be 1079.779 KW and 693.5628 KVAR respectively. The minimum bus voltage is occurred at bus 59 with a magnitude of 0.8402 p.u and from 193 total buses, the voltage profile of 130 buses is below the acceptable voltage level. After integrating D-STATCOM with the distribution system, 45.916% real and 45.621% reactive power losses were reduced. In addition to this, all bus voltages were kept within the acceptable range and the low voltage profile on bus 59 was improved from 0.84022p.u to 0.9541p.u.
Finally, a cost analysis was conducted to determine the economic feasibility of the solution. The cost analysis indicates that an investment cost of 15.425 million ETB is required to install a D-STATCOM size of 5414 KVAR and it takes 2.17 years to return this cost. Based on the results, it can be concluded that the proposed system is effective in reducing power loss and improving the voltage profile of the distribution system.

5.2. Recommendation

This research work provides some benefits to both utility and customers, for example, this reduces the active and reactive power loss and improves the voltage at the customer side to the desired level. This will bring a reliable and secure power supply to the customer and give satisfaction. So, I recommend EEU implement this method in the Debre Berhan distribution system and benefit from it.

5.3. Suggestions for Future Work

- Further analysis can be done by considering the simultaneous placement of DG and D-STATCOM.
- Further researchers could accomplish this by considering other recent optimization algorithms or hybrid DA.

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APPENDIXES

Appendix A: Interruption Data for Debrebirhan Substation No-1

Line		Dashen Brewery 33KV	Habesha Brewery 33KV	Row-Rank 33KV	Aliyu-amba 33KV	Ankober 15KV	Blanket Factory	Sheno 15KV	Mendida 15KV
Sep	F	33	0	11	38	29	0	22	12
	D	85:37:12	0	0:48:00	28:21:36	44:02:24	0	9:27:36	5:34:12
Oct	F	12	6	5	41	32	5	24	25
	D	1:56:24	5:09:00	2:32:24	19:15:36	20:40:24	6:25:12	12:01:36	12:13:48
Nov	F	13	17	16	30	19	2	31	31
	D	5:07:48	17:55:12	1:07:12	27:06:00	8:09:00	0:20:24	11:34:48	7:21:36
Dec	F	13	7	8	36	8	4	16	0
	D	9:43:48	11:38:48	5:24:36	14:55:48	3:36:00	2:57:00	1:03:00	0
Jun	F	7	5	11	14	12	4	13	12
	D	4:01:12	1:44:24	4:04:12	9:31:12	6:46:12	3:39:36	8:21:36	8:08:00
Feb	F	7	16	6	71	30	0	19	22
	D	25:30:00	5:40:00	17:45:00	17:05:24	8:52:48	0	9:27:36	19:53:24
Mar	F	15	36	23	79	27	1	6	39
	D	0:11:00	22:07:12	13:00:00	48:00:00	20:48:00	0:18:00	4:00:00	37:00:00
Apr	F	14	3	3	64	27	5	2	29
	D	30:12:36	0:09:00	08:07:48	22:14:24	12:36:00	8:12:00	00:06:00	28:51:00
May	F	7	2	7	76	37	2	2	16
	D	0:39:36	03:06:00	00:20:24	27:30:00	6:29:24	00:47:24	00:58:48	3:22:24
June	F	10	12	29	50	39	0	1	38
	D	31:57:36	7:00:36	02:09:36	37:42:00	3:31:48	0	04:00:00	23:21:12
July	F	22	1	18	73	36	3	5	23
	D	32:39:36	5:19:48	6:08:24	56:46:48	10:33:36	0: 04:48	10:32:24	9:21:36
Aug	F	14	4	13	75	51	5	1	34
	D	12:06:00	01:54:00	03:54:00	44:31:12	35:48:36	02:18:00	00:03:00	12:34:48
Total interruption	F_T	**167**	**109**	**150**	**647**	**347**	**25**	**49**	**281**
	D_T	240:30:48	81:44:00	65:21:36	353:00:00	181:53:48	25:02:24	71:35:24	167:42:00

Appendix B: Conductor Datasheet

CONDUCTOR DATA SHEET
ALL ALUMINIUM CONDUCTOR (AAC)

DIN Spec.

Area		Equivalent Copper Area	Stranding and wire diameter	Overall Diameter	Weight	Rated Strength	Maximum dc resistance at 20 °C
Nominal	Actual						
mm^2	mm^2	mm^2	mm	mm	kg/km	kN	Ω /km
16	15.89	10	7/1.7	5.1	43	2.84	1.8017
25	24.25	15	7/2.1	6.3	66	4.17	1.1806
35	34.36	21	7/2.5	7.5	94	5.78	0.8332
50	49.48	30	7/3.0	9.0	135	7.94	0.5786
50	48.36	29	19/1.8	9.0	133	8.45	0.5948
70	65.82	40	19/2.10	10.5	181	11.32	0.4370
95	93.27	57	19/2.50	12.5	256	15.68	0.3084
120	117.00	71	19/2.80	14.0	322	18.78	0.2459
150	147.10	90	37/2.25	15.75	406	25.30	0.1960
185	181.60	111	37/2.50	17.50	500	30.54	0.1588
240	242.5	148	61/2.25	20.25	670	39.51	0.1192
300	299.4	183	61/2.50	22.50	827	47.70	0.09651
400	400.1	244	61/2.89	26.01	1104	60.86	0.07222
500	499.8	305	61/3.23	29.07	1379	74.67	0.05782
625	626.2	385	91/2.96	32.56	1732	95.25	0.04625
800	802.1	489	91/3.35	36.85	2218	118.39	0.03611
1000	999.7	610	91/3.74	41.14	2767	145.76	0.02897

Appendix C: EEU Energy Tariff

Tariff amendment	As of Dec. 18 onward	As of Dec. 19 onward	As of Dec. 20 onward	As of Dec. 21 onward
Tariff Category kwh/month	Birr/kwh	Birr/kwh	Birr/kwh	Birr/kwh
1.Residential tariff block				
1.1 1st block Up to 50kwh	0.2730	0.2730	0.2730	0.2730
1.2 2nd block Up to100kwh	0.4591	0.5617	0.6644	0.7670
1.3 3rd block Up to 200kwh	0.7807	1.0622	1.3436	1.6250
1.4 4th block Up to 300kwh	0.9125	1.2750	1.6375	2.0000
1.5 5th block Up to 400 kwh	0.9750	1.3833	1.7917	2.2000
1.6 6th block Up to 500kwh	1.0423	1.4965	1.9508	2.4050
1.7 7th block Above 500kwh	1.1410	1.5877	2.0343	2.4810
2. General Tariff				
2.1 Flat Rate	1.0352	1.3982	1.7611	2.1240
3. Low Voltage Industry Tariff				
3.1 Flat Rate	0.8161	1.0544	1.2927	1.5310
3.2 Demand Charge rate	50.0000	100.00	150.0000	200.0000
4. Medium Voltage Industry Tariff. 15kv & 33kv				
4.1 Flat Rate	0.6047	0.8008	0.9969	1.1930
4.2 Demand Charge rate	36.8850	73.7700	110.6550	147.5400
5. High Voltage Industry Tariff. Above 66kv				
5.1 Flat Rate	0.5174	0.6540	0.7911	0.9280
5.2 Demand Charge rate	21.9100	43.8200	65.7300	87.6400
6. Street Light Tariff				
6.1 Flat Rate	1.0352	1.3982	1.7611	2.1240
7. Bulk Supply Tariff				
7.1 Demand Charge rate per kw	39.2908	78.5815	117.8723	157.1600
7.2 Generation Tariff. Monthly per kwh	0.2218	0.4435	0.6653	0.8870

Appendix D: Line Data for Aliyu-amba Feeder

Bus No	Sending end	Receiving end	Conductor type	Length(Km)	Resistance(Ω)	Reactance(Ω)
1	1	2	AAC-50	1.2	0.6942	0.4164
2	2	3	>>	1.47	0.8504	0.5101
3	3	4	>>	3.26	1.8859	1.1312
4	4	5	AAC-95	0.05	0.0154	0.0162
5	5	6	>>	1.5	0.4628	0.4866
6	6	7	>>	0.05	0.0154	0.0162
7	7	8	AAC-50	0.48	0.2777	0.1666
8	8	9	>>	1.16	0.6711	0.4025
9	9	10	>>	3.2	1.8512	1.1104
10	10	11	>>	0.2	0.1157	0.0694
11	11	12	>>	0.9	0.5207	0.3123
12	12	13	>>	0.2	0.1157	0.0694
13	13	14	>>	1.5	0.8678	0.5205
14	14	15	>>	0.3	0.1736	0.1041
15	15	16	>>	0.4	0.2314	0.1388
16	16	17	>>	2.6	1.5041	0.9022
17	17	18	>>	0.4	0.2314	0.1388
18	18	19	>>	0.1	0.0579	0.0347
19	19	20	>>	1	0.5785	0.347
20	20	21	>>	0.4	0.2314	0.1388
21	21	22	>>	0.1	0.0579	0.0347
22	22	23	AAC-95	2.2	0.6787	0.7137
23	23	24	>>	0.4	0.1234	0.1298
24	24	25	AAC-50	0.1	0.0579	0.0347
25	25	26	>>	0.2	0.1157	0.0694
26	26	27	AAC-95	1.5	0.4628	0.4866
27	27	28	AAC-50	0.2	0.1157	0.0694
28	28	29	>>	0.6	0.3471	0.2082
29	29	30	>>	1	0.5785	0.347
30	30	31	>>	0.1	0.0579	0.0347
31	31	32	>>	1.2	0.6942	0.4164
32	32	33	>>	2.9	1.6777	1.0063
33	33	34	>>	0.8	0.4628	0.2776
34	34	35	>>	0.1	0.0579	0.0347
35	35	36	>>	0.9	0.5207	0.3123

36	36	37	>>	0.6	0.3471	0.2082
37	37	38	>>	0.7	0.405	0.2429
38	38	39	>>	0.3	0.1736	0.1041
39	39	40	>>	1.2	0.6942	0.4164
40	40	41	>>	0.25	0.1446	0.0868
41	41	42	>>	0.1	0.0579	0.0347
42	42	43	>>	0.35	0.2025	0.1215
43	43	44	AAC-95	0.6	0.1851	0.1947
44	44	45	AAC-50	0.3	0.1736	0.1041
45	45	46	>>	0.3	0.1736	0.1041
46	46	47	AAC-95	0.1	0.0309	0.0324
47	47	48	>>	0.7	0.216	0.2271
48	48	49	AAC-50	0.4	0.2314	0.1388
49	49	50	>>	0.1	0.0579	0.0347
50	50	51	AAC-95	1.3	0.4011	0.4217
51	51	52	>>	0.3	0.0926	0.0973
52	52	53	>>	0.05	0.0154	0.0162
53	53	54	>>	1	0.3085	0.3244
54	54	55	>>	1.3	0.4011	0.4217
55	55	56	>>	0.8	0.2468	0.2595
56	56	57	>>	1.2	0.3702	0.3893
57	57	58	>>	0.8	0.2468	0.2595
58	58	59	>>	0.9	0.2777	0.292
59	1	60	AAC-50	5.47	3.1644	1.8981
60	60	61	>>	1.1	0.6364	0.3817
61	61	62	AAC-95	7.07	2.1811	2.2936
62	62	63	AAC-50	7.1	4.1074	2.4637
63	63	64	>>	7.19	4.1594	2.4949
64	64	65	>>	0.1	0.0579	0.0347
65	65	66	>>	0.7	0.405	0.2429
66	66	67	>>	0.1	0.0579	0.0347
67	67	68	>>	0.6	0.3471	0.2082
68	68	69	>>	8.9	5.1487	3.0883
69	69	70	>>	0.4	0.2314	0.1388
70	61	71	>>	3.77	2.1809	1.3082
71	62	72	>>	0.3	0.1736	0.1041
72	72	73	AAC-95	1.1	0.3394	0.3569
73	73	74	>>	1.8	0.0555	0.0584
74	74	75	>>	0.2	0.0617	0.0649

75	75	76	>>	0.6	0.1851	0.1947
76	76	77	>>	0.2	0.0617	0.0649
77	73	78	AAC-50	0.3	0.1736	0.1041
78	74	79	>>	0.1	0.0579	0.0347
79	72	80	AAC-95	0.2	0.0617	0.0649
80	80	81	>>	0.3	0.0926	0.0973
81	81	82	AAC-50	0.1	0.0579	0.0347
82	63	83	>>	0.26	0.1504	0.0902
83	83	84	>>	2	1.157	0.694
84	84	85	AAC-95	3	0.9255	0.9732
85	85	86	AAC-50	0.4	0.2314	0.1388
86	85	87	AAC-95	3.2	0.9872	1.0381
87	64	88	>>	0.1	0.0309	0.0324
88	88	89	>>	0.8	0.2468	0.2595
89	89	90	>>	1.3	0.4011	0.4217
90	90	91	AAC-50	0.4	0.2314	0.1388
91	91	92	AAC-95	3.3	1.0181	1.0706
92	65	93	AAC-50	0.2	0.1157	0.0694
93	66	94	>>	0.1	0.0579	0.0347
94	67	95	>>	9.4	5.4379	3.2618
95	2	96	>>	0.18	0.1041	0.0625
96	96	97	>>	0.03	0.0174	0.0104
97	97	98	>>	0.13	0.0752	0.0451
98	98	99	>>	0.03	0.0174	0.0104
99	97	100	>>	0.12	0.0694	0.0416
100	3	101	>>	0.09	0.0521	0.0312
101	101	102	>>	0.04	0.0231	0.0139
102	4	103	>>	0.1	0.0579	0.0347
104	104	105	>>	0.25	0.1446	0.0868
105	105	106	AAC-95	0.34	0.1049	0.1103
106	106	107	AAC-50	0.52	0.3008	0.1804
107	103	108	>>	0.28	0.162	0.0972
108	104	109	>>	0.2	0.1157	0.0694
109	7	110	>>	0.4	0.2314	0.1388
110	110	111	AAC-95	0.44	0.1357	0.1427
111	111	112	>>	0.28	0.0864	0.0908
112	110	113	AAC-50	0.01	0.0058	0.0035
113	113	114	>>	0.18	0.1041	0.0625
114	113	115	>>	1.03	0.5959	0.3574

115	10	116	>>	0.1	0.0579	0.0347
116	116	117	>>	0.2	0.1157	0.0694
117	11	118	>>	0.6	0.3471	0.2082
118	15	119	>>	0.8	0.4628	0.2776
119	15	120	>>	0.1	0.0579	0.0347
120	120	121	>>	0.08	0.0463	0.0278
121	121	122	>>	0.17	0.0983	0.059
122	122	123	>>	0.2	0.1157	0.0694
123	16	124	>>	0.1	0.0579	0.0347
124	17	125	>>	0.1	0.0579	0.0347
125	19	126	>>	0.8	0.4628	0.2776
126	126	127	AAC-95	0.5	0.1543	0.1622
127	127	128	AAC-50	0.8	0.4628	0.2776
128	126	129	>>	0.4	0.2314	0.1388
129	20	130	>>	0.1	0.0579	0.0347
130	130	131	>>	0.8	0.4628	0.2776
131	26	132	>>	0.1	0.0579	0.0347
132	28	133	>>	0.1	0.0579	0.0347
133	29	134	>>	0.1	0.0579	0.0347
134	31	135	>>	0.1	0.0579	0.0347
135	32	136	AAC-95	0.7	0.216	0.2271
136	33	137	AAC-50	2	1.157	0.694
137	137	138	AAC-95	0.7	0.216	0.2271
138	138	139	AAC-50	1.5	0.8678	0.5205
139	137	140	>>	0.04	0.0231	0.0139
140	34	141	>>	0.1	0.0579	0.0347
141	141	142	>>	0.07	0.0405	0.0243
142	37	143	>>	0.1	0.0579	0.0347
143	38	144	>>	0.1	0.0579	0.0347
144	39	145	>>	0.9	0.5207	0.3123
145	145	146	>>	0.4	0.2314	0.1388
146	146	147	>>	0.1	0.0579	0.0347
147	147	148	AAC-95	0.2	0.0617	0.0649
148	148	149	AAC-50	0.3	0.1736	0.1041
149	149	150	>>	0.19	0.1099	0.0659
150	150	151	>>	0.8	0.4628	0.2776
151	146	152	>>	0.1	0.0579	0.0347
152	147	153	AAC-95	0.2	0.0617	0.0649
153	153	154	AAC-50	0.2	0.1157	0.0694

154	154	155	>>	0.1	0.0579	0.0347
155	153	156	AAC-95	2.7	0.833	0.8759
156	148	157	AAC-50	0.1	0.0579	0.0347
157	150	158	>>	0.1	0.0579	0.0347
158	40	159	>>	3.2	1.8512	1.1104
159	159	160	>>	0.8	0.4628	0.2776
160	160	161	>>	0.5	0.2893	0.1735
161	161	162	>>	2	1.157	0.694
162	41	163	>>	1.2	0.6942	0.4164
163	42	164	>>	0.5	0.2893	0.1735
164	164	165	>>	0.3	0.1736	0.1041
165	165	166	>>	0.5	0.2893	0.1735
166	43	167	>>	0.4	0.2314	0.1388
167	167	168	>>	0.2	0.1157	0.0694
168	167	169	>>	0.6	0.3471	0.2082
169	46	170	>>	0.2	0.1157	0.0694
170	47	171	AAC-95	0.9	0.2777	0.292
171	171	172	>>	0.9	0.2777	0.292
172	172	173	>>	0.1	0.0309	0.0324
173	172	174	AAC-50	0.4	0.2314	0.1388
174	48	175	>>	0.4	0.2314	0.1388
175	49	176	>>	0.2	0.1157	0.0694
176	176	177	AAC-95	0.1	0.0309	0.0324
177	177	178	AAC-50	0.5	0.2892	0.1735
178	178	179	AAC-95	0.4	0.1234	0.1298
179	179	180	AAC-50	2.2	1.2727	0.7634
180	180	181	>>	0.3	0.1736	0.1041
181	176	182	>>	0.2	0.1157	0.0694
182	180	183	>>	0.1	0.0579	0.0347
183	51	184	AAC-95	0.14	0.0432	0.0454
184	184	185	>>	2	0.617	0.6488
185	52	186	>>	0.3	0.0926	0.0973
186	186	187	>>	1	0.3085	0.3244
187	187	188	>>	4	1.234	1.2976
188	188	189	>>	0.1	0.0309	0.0324
189	188	190	>>	0.4	0.1234	0.1298
190	54	191	>>	0.2	0.0617	0.0649
191	55	192	>>	0.99	0.3054	0.3212
192	56	193	>>	1.13	0.3486	0.3666

Appendix E: Load Data for Aliyu-amba Feeder

Bus No	Transformer rating(KVA)	P(KW)	Q(KVAR)	Bus No	Transformer rating(KVA)	P(KW)	Q(KVAR)
1	0	0	0	98	200	160	120
2	0	0	0	99	200	160	120
3	0	0	0	100	200	160	120
4	0	0	0	101	50	40	30
5	100	80	60	102	100	80	60
6	50	40	30	103	0	0	0
7	0	0	0	104	0	0	0
8	200	160	120	105	315	252	189
9	50	40	30	106	200	160	120
10	0	0	0	107	100	80	60
11	0	0	0	108	50	40	30
12	50	40	30	109	50	40	30
13	25	20	15	110	0	0	0
14	50	40	30	111	25	20	15
15	0	0	0	112	100	80	60
16	50	40	30	113	0	0	0
17	0	0	0	114	50	40	30
18	100	80	60	115	25	20	15
19	0	0	0	116	50	40	30
20	0	0	0	117	200	160	120
21	100	80	60	118	50	40	30
22	25	20	15	119	100	80	60
23	50	40	30	120	200	160	120
24	200	160	120	121	200	160	120
25	25	20	15	122	200	160	120
26	0	0	0	123	200	160	120
27	50	40	30	124	25	20	15
28	0	0	0	125	50	40	30
29	0	0	0	126	0	0	0
30	50	40	30	127	100	80	60
31	0	0	0	128	100	80	60
32	25	20	15	129	25	20	15
33	0	0	0	130	100	80	60
34	0	0	0	131	50	40	30
35	100	80	60	132	200	160	120

36	100	80	60	133	630	504	378
37	100	80	60	134	100	80	60
38	0	0	0	135	200	160	120
39	0	0	0	136	100	80	60
40	0	0	0	137	50	40	30
41	0	0	0	138	50	40	30
42	0	0	0	139	200	160	120
43	0	0	0	140	50	40	30
44	200	160	120	141	100	80	60
45	50	40	30	142	100	80	60
46	0	0	0	143	50	40	30
47	0	0	0	144	100	80	60
48	0	0	0	145	50	40	30
49	50	40	30	146	0	0	0
50	200	160	120	147	100	80	60
51	0	0	0	148	100	80	60
52	0	0	0	149	100	80	60
53	100	80	60	150	0	0	0
54	0	0	0	151	315	252	189
55	0	0	0	152	200	160	120
56	0	0	0	153	200	160	120
57	50	40	30	154	50	40	30
58	50	40	30	155	100	80	60
59	100	80	60	156	100	80	60
60	25	20	15	157	100	80	60
61	0	0	0	158	100	80	60
62	0	0	0	159	50	40	30
63	0	0	0	160	50	40	30
64	0	0	0	161	50	40	30
65	0	0	0	162	200	160	120
66	0	0	0	163	100	80	60
67	200	160	120	164	100	80	60
68	25	20	15	165	100	80	60
69	200	160	120	166	50	40	30
70	100	80	60	167	0	0	0
71	200	160	120	168	50	40	30
72	0	0	0	169	50	40	30
73	0	0	0	170	50	40	30
74	25	20	15	171	50	40	30

75	25	20	10	172	0	0	0
76	100	80	60	173	100	80	60
77	50	40	30	174	50	40	30
78	100	80	60	175	25	20	15
79	50	40	30	176	0	0	0
80	100	80	60	177	315	252	189
81	50	40	30	178	50	40	30
82	50	40	30	179	50	40	30
83	100	80	60	180	0	0	0
84	100	80	60	181	50	40	30
85	0	0	0	182	25	20	15
86	100	80	60	183	100	80	60
87	100	80	60	184	100	80	60
88	25	20	15	185	100	80	60
89	100	80	60	186	100	80	60
90	100	80	60	187	100	80	60
91	100	80	60	188	0	0	0
92	25	20	15	189	50	40	30
93	50	40	30	190	50	40	30
94	200	160	120	191	50	40	30
95	25	20	15	192	200	160	120
96	200	160	120	193	100	80	60
97	0	0	0				

Appendix F: Subprogram for BIBC Matrix

```
function [bibc_matrix]=bibc_gen(linedata,busdata)
%           nbus=193;%input('enter number of bus:');
%             [linedata]=xlsread('Feederdata.xlsx','linedata');
%             busdata=xlsread('Feederdata.xlsx','busdata');

num_of_lines=length(linedata(:,2));% why 2 it change to 1
num_of_bus=length(busdata(:,1));
from_node=linedata(:,2);
to_node=linedata(:,3);
connect_matrix_lf=sparse(1:num_of_lines, from_node, ones(num_of_lines,
1), num_of_lines, num_of_bus);
connect_matrix_lt=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);                % all
element are one except diagonal it is zero
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);                                    %
columen matrix

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%  h = view(biograph(final_connect_mat)) % This will create a diagram of
the bus connection (if required)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%
for ind=1:num_of_bus
    node_order_val(:,ind)=sort([zero_matrix1(1:(num_of_bus-...
        length(graphtraverse(final_connect_mat,ind))));...
        graphtraverse(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;
```

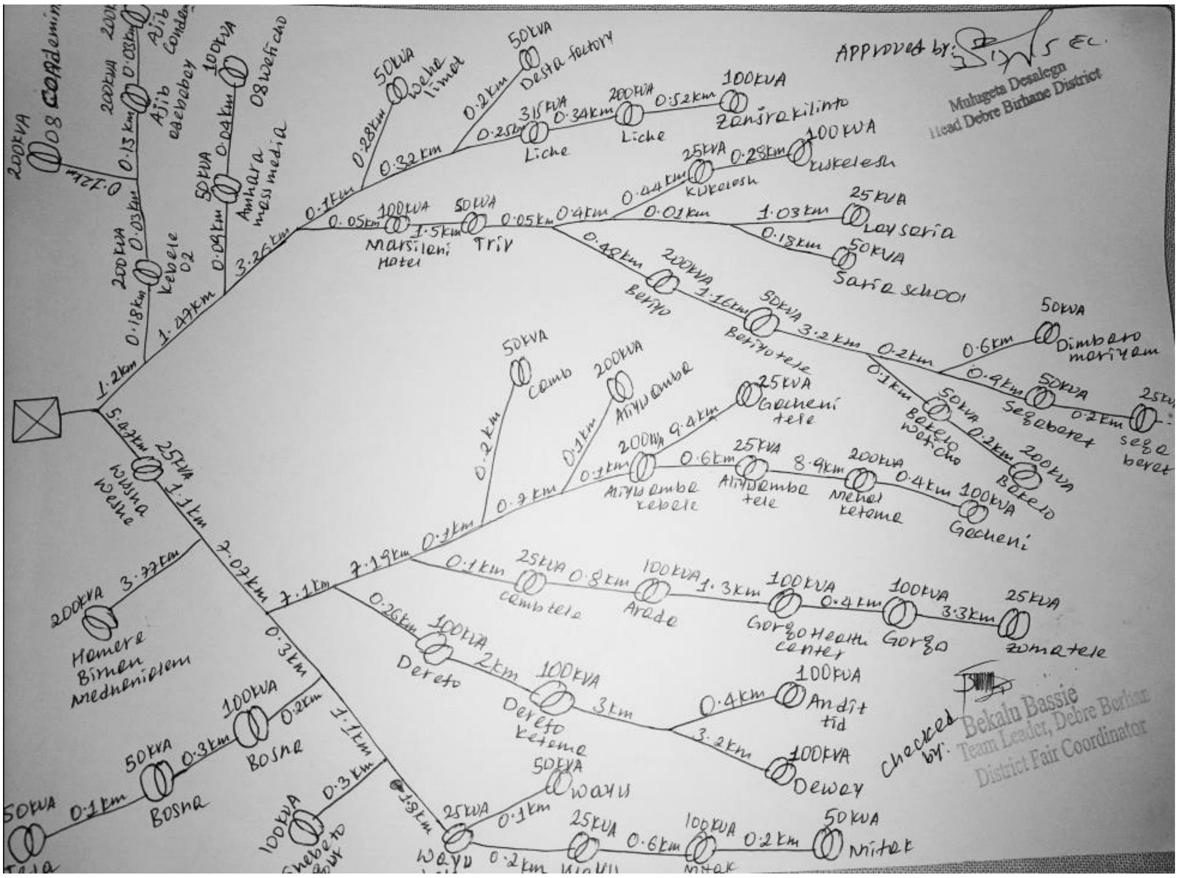
Appendix G: Base-Case Load Flow Algorithm Program

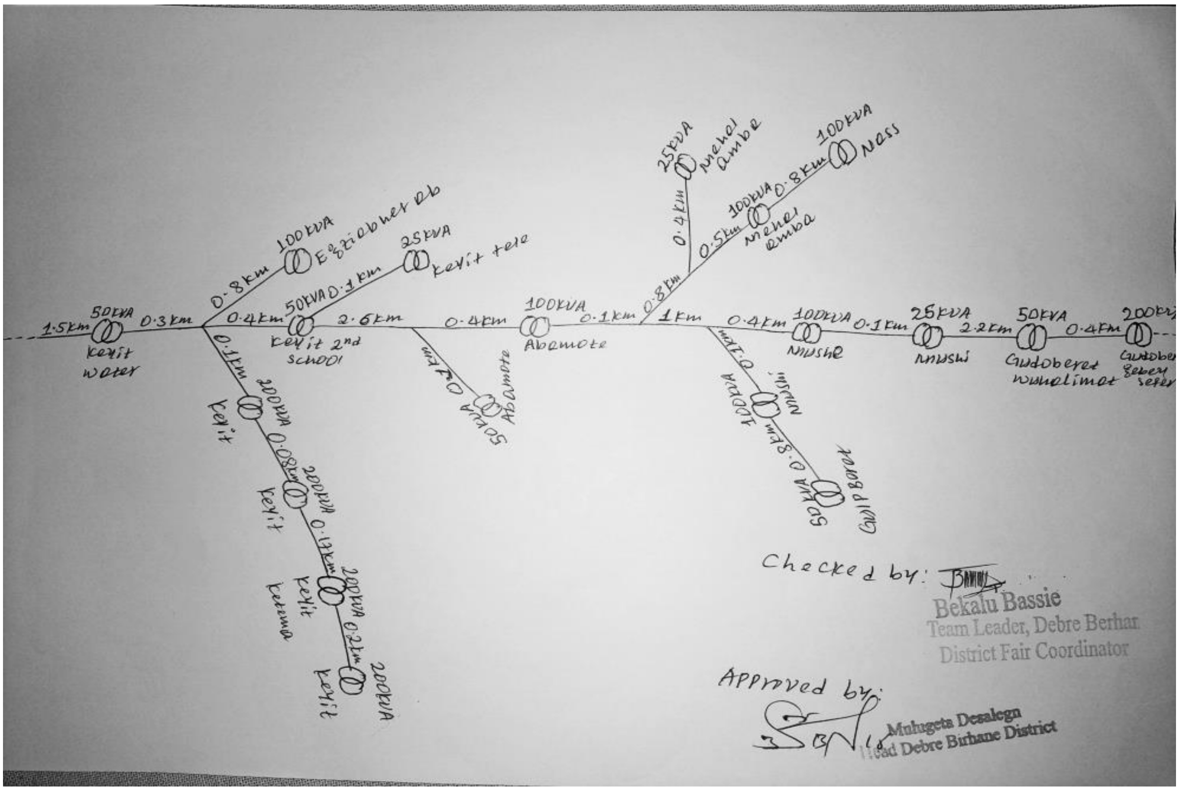
```
function [finalres_out]=load_flow_base_case

source_num=[1];
% Read the line and bus data from excel file
 LINEDATA=xlsread('Feederdata.xlsx','linedata');
 BUSDATA=xlsread('Feederdata.xlsx','busdata');

baseKV=33;baseMVA=100;
PBASE=baseMVA*1000;                              %  Change to KVA
ZBASE=(baseKV^2)/baseMVA;                        % Base impedance
busdata_value=BUSDATA;linedata_value=LINEDATA;

linedata_value(:,4:5)=linedata_value(:,4:5)/ZBASE;          % per unit
conversion
resistance_val=linedata_value(:,4);                         % per unit
resistance
reactance_val=linedata_value(:,5);                          % per unit
reactance
perunit_imped=complex(resistance_val,reactance_val);
busdata_value(:,2:3)=(busdata_value(:,2:3)/PBASE);           % Per unit
conversion
imped_value=perunit_imped;
[bibc_matrix]=bibc_gen(linedata_value,busdata_value);       % calling
bibc matrix

bibc_matrix(source_num,:)=[];
bibc_matrix(:,source_num)=[];

final_bibc_matrix=bibc_matrix';
% diag of collum vector is happend
final_bcbv_matrix=final_bibc_matrix'*diag(perunit_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);                         %
193x1 matrix
final_load_matrix=(complex_load_d-complex_load_g);                     %
ingected power Pi=Pd-Pg
```

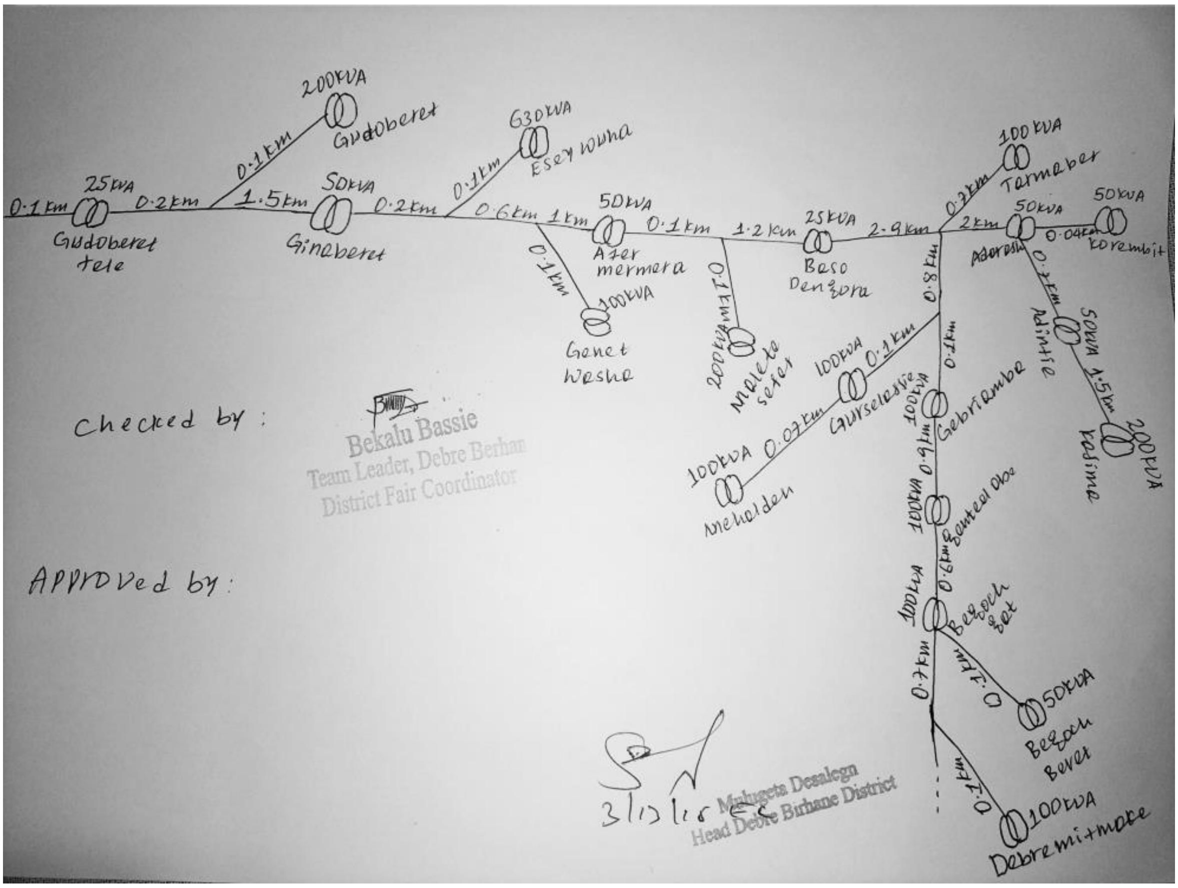
```
final_load_matrix(length(source_num))=[];                              %
out of source node
initial_volt_value=ones(size(busdata_value,1)-length(source_num),1);   %
192x1 initial bus voltage 1.0 p.u
voltage_drop_value=initial_volt_value;

% convergency with max iter
max_iter=50;
% error_volt_tolr =0.2e-3; % maximum iteration
% while max_iter==50 && error_volt_tolr<=0.2e-3
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 drop w.r.t. substation bus.
    voltage_drop_value=initial_volt_value-volt_drop_each;
    old_volt1=(old_volt);
    new_volt=(voltage_drop_value);
    % tolerance must defineend
    error_volt_tolr=max(abs(old_volt1-new_volt));
%% must be defien max error
end
% end
final_volt_data=[ones(length(source_num),1);voltage_drop_value];
% voltage profile
% ????
locvoltm=find(final_volt_data>1);                  %if voltage is above 1 pu
set as 1 pu
final_volt_data(locvoltm)=1;
from_node=linedata_value(:,2);
to_node=linedata_value(:,3);
bus_num=linedata_value(:,1);
for ind=1:length(from_node)
    %each branch voltage drop
    volt_diff_value(ind,:)=final_volt_data(from_node(ind))-
final_volt_data(to_node(ind));
end
```

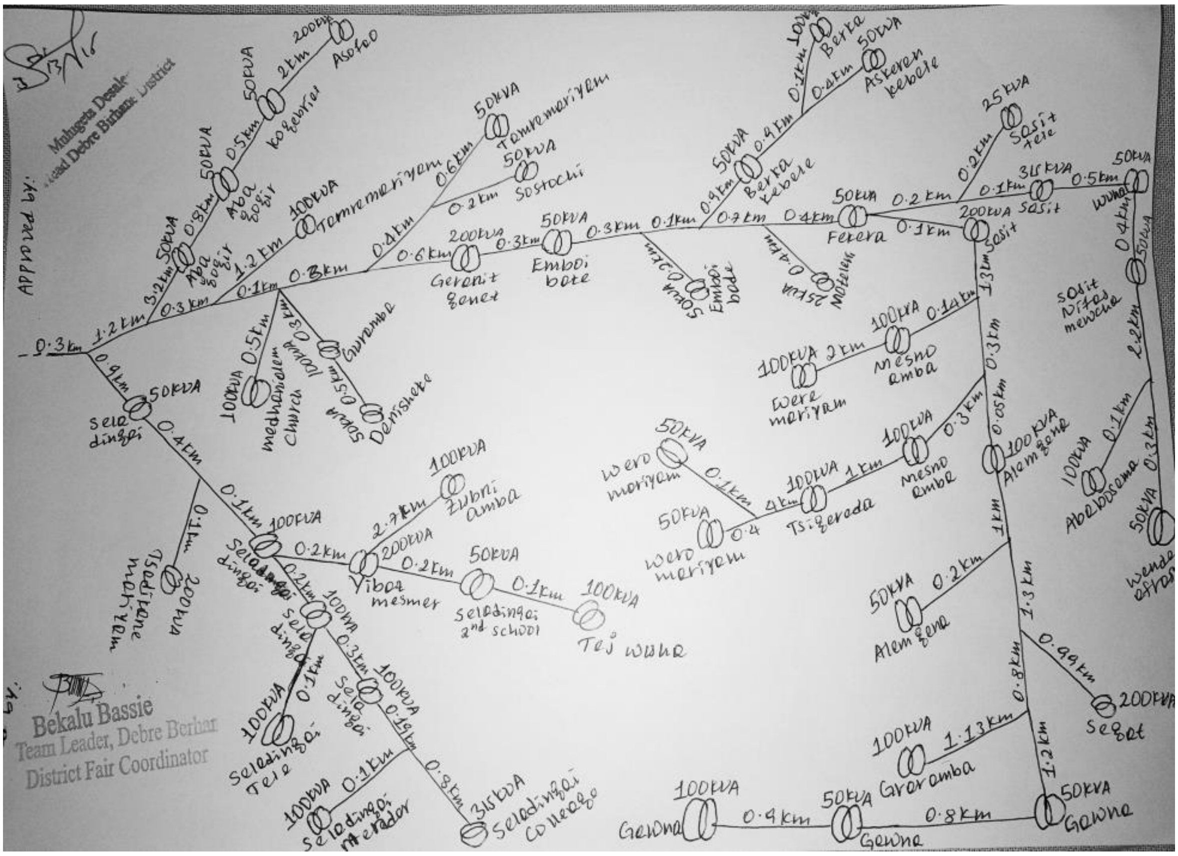
```
volt_diff_value1=abs(volt_diff_value); % magnitude of voltage drop for
each branch
%% Loss calculation
% ploss=sum(abs(IB).^2.*resistance_val)*10^5;
ploss=((volt_diff_value1.^2).*resistance_val)./(abs(imped_value).*abs(imp
ed_value))*10^5; % Each Line Loss in kWs
loc1=find(~(isnan(ploss)));
% qloss=sum(abs(IB).^2.*reactance_val)*10^5;
qloss=((volt_diff_value1.^2).*reactance_val)./(abs(imped_value).*abs(impe
d_value))*10^5; % Each Line Loss in kVAr
loc2=find(~(isnan(qloss)));
%apparent power of the branch
Br_power(:,1)=volt_diff_value(:,1).*conj(IB);
total_lossp=sum(ploss(loc1));
total_lossq=sum(qloss(loc2));
final_voltage=abs(final_volt_data); %
CVD=sum((1-final_voltage(:,1)).^2);
[V_min,bus_nu]=min(final_voltage);

finalres_out{1}=total_lossp;
finalres_out{2}=total_lossq;
finalres_out{3}=final_voltage;
finalres_out{4}=ploss;
finalres_out{5}=qloss;
finalres_out{6}=CVD;

finalres_out{7}=V_min;
finalres_out{8}=bus_nu;
```

Appendix H: Single Line Diagram of Aliyu-amba Feeder






200KVA
Gudoberet
630KVA
Esey wuha
100KVA
Termeber
25KVA
Gudoberet tele
50KVA
Gineberet
50KVA
Azer mermera
100KVA
Genet Weshe
200KVA
Melete Setet
25KVA
Beso Denzora
50KVA
Korembit
Mintie
200KVA
Kedime
100KVA
Gurselassie
100KVA
Meheldeh
Gebriembe
100KVA
Begoch bet
50KVA
Begoch Beret
100KVA
Debremitmake
Checked by:
Approved by:
Bekalu Bassie
Team Leader, Debre Berhan
District Fair Coordinator
Mulugeta Desalegn
Head Debre Birhane District


Approved by:
Mulugeta Desalegn
Head Debre Birhane District
200KVA
Asoteo
50KVA
Kogewrat
50KVA
Aba Gogir
100KVA
Temremeriyem
50KVA
Temremeriyem
50KVA
Sostochi
200KVA
Gerenit genet
50KVA
Emboi bote
50KVA
Berta kebele
50KVA
Askeren kebele
25KVA
Sasit tele
315KVA
Sasit
50KVA
Wuha
200KVA
Sasit
50KVA
Ferera
50KVA
Seladingai
100KVA
Werq meriyem
100KVA
Mesno Emba
100KVA
Tsigereda
50KVA
Wero meriyem
100KVA
Alem gena
50KVA
Alem gena
100KVA
Zubri amba
100KVA
Yibra mesmer
50KVA
Seladingai 2nd school
100KVA
Tej wuha
200KVA
Tsadkane Mariyem
100KVA
Seladingai tele
315KVA
Seladingai college
200KVA
Segbet
100KVA
Greramba
100KVA
Gewne
50KVA
Gewne
50KVA
Gewne
Bekalu Bassie
Team Leader, Debre Berhan
District Fair Coordinator