

Particle Swarm Optimization Based Distribution Static Compensator
Placement for Loss Minimization and Voltage Profile Improvement.

(A case study of Sabbata-I Substation outgoing Feeder)



Bikila Tesfa Shifera

A Thesis Submitted to
The Department of Electrical Power and Control Engineering
School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Masters
of Science in Electrical Power Engineering

Office of Graduate Studies
Adama Science and Technology University

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Adama, Ethiopia

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Declaration

This master's thesis, " Particle Swarm Optimization Based Distribution Static Compensator Placement for Loss Minimization and Voltage Profile Improvement," is my original work. That has not been submitted to any other university for the award of an academic degree, diploma, or certificate. All sources of information used in this thesis have been properly acknowledged with citations.

Name of the Student

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I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “Particle Swarm Optimization Based Distribution Static Compensator Placement for Loss Minimization and Voltage Profile Improvement” prepared under my guidance by Bikila Tesfa Shifera submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power Engineering. Therefore, I recommend the submission of a revised version of the thesis to the department following the applicable procedure.

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I, the advisor of the thesis “Particle Swarm Optimization Based Distribution Static Compensator Placement for Loss Minimization and Voltage Profile Improvement” and developed by Bikila Tesfa, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned members of the board of Examiners of the thesis by Bikila Tesfa have read and evaluated the thesis entitled “Particle Swarm Optimization Based Distribution Static Compensator Placement for Loss Minimization and Voltage Profile Improvement” 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 Masters of Science in Electrical Power Engineering.

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Table of Contents

Declaration.....	i
Recommendation	ii
Approval Sheet	iii
ACKNOWLEDGMENT	iv
Table of Contents.....	v
List of Tables	viii
List of Figures and Illustrations.....	ix
List of Acronyms and Abbreviations.....	x
ABSTRACT	xi
CHAPTER ONE.....	1
INTRODUCTION	1
1.1 Background of the Study	1
1.2 Statement of the Problem	4
1.3 Objectives	5
1.3.1 General Objective	5
1.3.2 Specific Objectives	5
1.4 Scope and Limitation of the Thesis	5
1.5 Significance of the Study.....	6
1.6 The Organization of the Thesis	6
CHAPTER TWO.....	7
BASIC THEORIES AND LITERATURE REVIEW	7
2.1 Electrical Power Distribution System.....	7
2.1.1 Categories of Distribution System.....	8
2.1.2 Requirements of a Distribution System.....	11
2.1.3 Distribution System Power Loss and Voltage Drop.....	12
2.1.4 Type of Losses in Distribution System.....	12
2.1.5 Voltage Drop in a Distribution System	14
2.1.6 Techniques for Improving Distribution Systems Performance	18
2.1.7 Overview of Flexible AC Transmission System Devices	20
2.1.8 Application of FACTS Devices.....	22
2.2 Literature Review	23
CHAPTER THREE	27
SYSTEM DESCRIPTIONS AND METHODOLOGY	27
3.1 Introduction.	27

3.2 Data Collection	27
3.2.1 Sabbata one Substation	28
3.2.2 Substation Transformer Data	31
3.2.3 Capacity of the Outgoing feeders of Sabbata-I Substation	31
3.2.4 Length and Capacity of Each Feeder	32
3.2.5 Yearly Peak Load and Minimum Load of the Feeders	33
3.2.6 Sabbata-I Distribution Line Arrangements	34
3.2.7 Single Line Diagram Representation of the Selected Feeder	36
3.2.8 Line and Bus Data of the Feeder	37
3.3 The Selected Reactive Power Compensator	39
3.3.1 Distribution Static Compensator	40
3.3.2 Components of D-STATCOM	41
3.3.3 Basic Operating Principle of D-STATCOM	41
3.3.4 Applications of D-STATCOM	42
3.3.5 Mathematical Modeling of D-STATCOM	42
3.4 Radial Distribution System Power Flow Analysis	45
3.4.1 Backward/forwards Sweeping for Radial Distribution Load Flow Analysis	45
3.5 Particle Swarm Optimization	50
3.5.1 PSO Parameters	53
3.6 Optimal size and Location of DSTATCOM	56
3.6.1 Problem Formulation	56
3.6.2 Energy Loss Cost, Investment Cost, and Total Annual Cost Saving	59
CHAPTER FOUR	61
RESULT AND DISCUSSION	61
4.1 Introduction	61
4.2 Method for the Simulation Result.	62
4.3 The simulation Result before integration of DSTATCOM	62
4.3.1 Base Case Active Power Loss Simulation Result	62
4.3.2 Reactive Power Loss Simulation Result Before DSTATCOM Compensation ..	64
4.3.4 Voltage Stability Simulation Result Before DSTATCOM Compensation	67
4.4 The Simulation Result with Distribution Static Compensator	69
4.4.1 Active Power Loss with Integration of DSTATCOM	69
4.4.2 Reactive Power Loss with DSTATCOM Allocation	71
4.4.3 Voltage Profile Improvement After DSTATCOM Placement	73
4.4.4 Voltage Stability with DSTATCOM Installation	74

4.4.5 Total Annual Cost Saving After Installation of DSTATCOM.....	75
4.5 Overall Discussion of the Simulation Result.....	76
CHAPTER FIVE	78
CONCLUSION AND RECOMMENDATION	78
5.1 Conclusion.....	78
5.2 Recommendation.....	79
REFERENCES	81
Appendix A: Load demand on the Feeder.....	xii
Appendix B: Power Interruption Data.....	xiv
Appendix C: Feeder Data	xv

List of Tables

Table 2.1 FACTS Controllers role in distribution system Operation.....	22
Table 3.1 the transformer data of sabbata-I substation.....	31
Table 3.2 the general data of outgoing feeder from sebbata-I substation.....	31
Table 3.3 length of the feeder from the substation	32
Table 3.4 peak load and minimum load of the outgoing feeders during 2020	33
Table 3.5 Standard of conductor.....	35
Table 3.6 line and bus data of sabbata-12 feeder	37
Table 4.1 base case active and reactive feeder loss simulation result	62
Table 4.2 Base Case Voltage profile	66
Table 4.3 Base Case Voltage Stability Index	67
Table 4.4 Base Case simulation result summary	68
Table 4.5 the power loss simulation result summary after integration of DSTATCOM	72
Table 4.6 cost benefits summary	75
Table 4.7 summary of the simulation results.....	76
Table appendix-A: The Sample of monthly peak and minimum load of Sabbata-I substation outgoing feeder.....	xii
Table Appendix-B: The two years (2019&2020) power interruption data	xiv
Table Appendix-C: The sample of Sabbata-I substation feeder-12 data.....	xv

List of Figures and Illustrations

Figure 2.1 Single line diagram of a typical low-tension distribution system	7
Figure 2.2 Radial distribution systems	9
Figure 2.3 Ring main systems	10
Figure 2.4 Interconnected distribution system	11
Figure 2.5 One-line diagram and corresponding phasor diagram for an illustration of the voltage drop in a distribution system.....	15
Figure 3.1 Sebbata-I substation single line diagram.....	30
Figure 3.2 peak, average, and minimum load of each feeder	34
Figure 3.3 Overhead Conductor Arrangement of Sabbata-I Feeder.....	35
Figure 3.4 Sabbata-I substation feeder-12 single line diagram	36
Figure 3.5 DSTATCOM connected to a certain bus k [49].....	40
Figure 3.6 Operating Modes of D-STATCOM[50].....	41
Figure 3.7 Two bus radial distribution system	42
Figure 3.8 Two bus radial distribution system with D-STATCOM [53]	43
Figure 3.9 Simple radial Distribution Network	47
Figure 3.10 Concept of a searching point by PSO[57].....	51
Figure 3.11 PSO search mechanism in multidimensional search space representation[59]	53
Figure 4.1 Active power loss in each branch before compensation	64
Figure 4.2 Reactive power loss in each branch without DSTATCOM	65
Figure 4.3 Base Case Voltage profile of the selected feeder without compensation	66
Figure 4.4 Base Case Result Voltage profile of the selected feeder without compensation	68
Figure 4.5 Active power loss after integration of DSTATCOM.....	70
Figure 4.6 total power loss with and without DSTATCOM	70
Figure 4.7 Reactive power loss after integration of DSTATCOM.....	71
Figure 4.8 total power loss with and without DSTATCOM	72
Figure 4.9 Voltage Profile After DSTATCOM Placement	73
Figure 4.10 Voltage Stability Indices with DSTATCOM Compensation.....	74

List of Acronyms and Abbreviations

AAC	All Aluminum Conductor
AC	Ant Colony
AI	Artificial Intelligence
BFS	Backward Forward Sweep
DG	Distributed Generation
DT	Distribution Transformer
DSTATCOM	Distribution Static Compensator
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
GA	Genetic Algorithm
HSA	Harmony search algorithm
IEEE	Institute of electrical and electronics engineers
IPSO	Imperialist particle swarm optimization
IPFC	Interline power flow controller
ICA	Imperialist Competitive Algorithm
KVA	Kilo Volt Ampere
KVAr	Kilo Volt Ampere Reactive
KVL	Kirchhoff's Voltage Law
MV	Medium Voltage
MVA	Mega volt-ampere
PF	Power Factor
PSO	Particle swarm optimization
SCC	Short circuit capacity
SSSC	Static Synchronous Series Compensator
TS	Tabu search
SVC	Static var compensator
UPFC	Unified power flow controller
VSC	Voltage source converter

ABSTRACT

The distribution system is the end part of the electrical power system that delivers electric power to the load demand. The majority of power quality issues including losses, weak voltage profiles, voltage instability takes place in the distribution system. The primary concern of any electric utility is to meet rising load demand with high quality. Installing capacitor banks, network reconfiguration, distribution generation, and upgrading distribution cables have all been attempted to solve such kind of power quality issues. In this thesis work, the optimal size and placement of the distribution static compensator in the radial distribution system was used to reduce losses, improve voltage profile and voltage stability. The forward/backward sweep algorithm was used to do the load flow analysis of the existing system, and to evaluate whether the system is run efficiently or not. The voltage stability index has been used to identify the candidate buses for optimal placement of distributed static compensator, while the particle swarm optimization algorithm has been employed to determine the appropriate size and placement of the device. The study has been carried out on the Sabbata-one substation on the feeder which has 89 buses. The objective function of the thesis work was to reduce both active and reactive power, improve voltage profile and voltage stability by providing sufficient reactive power to the feeder. As a result, the optimal size of distributed static compensator that has been determined by particle swarm optimization was 1103.42kVar, whereas bus 76 is the appropriate location of the device. The result of the system has been showing that the total active power loss decrease from 403.0803kW to 334.2578kW, while reactive power loss decrease from 356.1287KVar to 296.778KVar. The percentage reduction in real and reactive power loss became 21%, and 20% respectively. The entire voltage profile of the feeder has been enhanced within the required standard level with the minimum bus voltage of 0.950001(p.u), and the voltage stability index has been improved with a minimum value of 0.8145(p.u). The total annual cost wastage due to power loss has been minimized after the integration of the distribution static compensator. As a result, the Ethiopian Electric Utility can save 55,872.5\$ per annum with a payback period of about one year, and the percentage of cost reduction due to system loss was about 35.82%.

Keywords: *Distribution system in Ethiopia, DSTATCOM placement, loss reduction, voltage stability index, PSO, voltage profile improvement.*

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Electrical energy is one of the important things that cannot be separated from daily human lives in the era of globalization and is widely employed in many aspects of modern life, including transportation, public service, industry, government, and residential.

A generation, transmission line, and distribution system are the three fundamental components of an electric power system, all of which have the primary objective of generating enough electrical energy, transferring it in adequate amounts, and delivering it to end-users with high quality. Electrical power system networks have become increasingly complex, dynamic, nonlinear, and susceptible to numerous forms of disturbances in recent years. The distribution system is the largest part of the power system, which is typically radial in configuration, and the most crucial connection among the electrical power system components. It is a part of the power system that delivers able electric power to different customers at their consumption stage. The distribution system delivers electric power to the end-user at its specified standard range. As a result, utilities should provide sustainable and cost-effective service while maintaining service voltages and power quality within defined limits. There are various power quality issues in electric power distribution networks due to different types of load available in varied ranges of energy consumption, over and under loading, equipment failure, and insulation failure.

The distribution system is an important component of the power system, as it is responsible for power losses and voltage constraints that affect load demand. The load current supplied from the source would increase in a highly overloaded distribution network, and the stress would lead the system to lose a lot of power and have an inappropriate voltage profile. The high R/X ratio in the distribution system also causes poor power quality in a distribution system. The major drawback of a high R/X ratio may cause voltage drop, lagging power factor, and instability in the system. In the radial distribution network, these challenges result in high power losses, poor voltage profiles, and network security issues [1].

The voltage at buses operates with a weak profile when the distribution feeders are far away from the distribution substation. This is one of the typical features of a distribution network. Especially around the industrial areas which faced critical loading, the system getting to voltage collapse. Due to high power losses and an undesirable voltage drop, the distribution

network's performance becomes unreliable. The bus voltage level varies with the drop in voltage level and the reactive power demand when the load demand changes. When the sending end reactive power falls short of the reactive power required by load demand, the bus voltage drops, affecting the interconnected system network. In another way, the ratio of reactance to resistance is very high in the distribution system which causes voltage drop and high power losses in the distribution network. Therefore, to enhance the voltage profile and reduce power loss an effective optimal size and placement of reactive power mitigation tool are required. As a result, the distribution system is the most powerful system part which is mainly responsible for high power loss. According to various study shows, 13 percent of the total electric power generated is misused due to distribution system losses [2].

The feeder of Sebbata-I substation is characterized by a radial distribution system, located far away from load centers, and a considerable distance in the distribution from the substation to the consumer may cause a decrease in voltage which results in some power losses. Some of the distribution networks are faced with voltage drop when the major disturbances occur at the system and the voltage operating near to their stability range under heavy load. It also has several consumers that are connected to the existing feeders. The overloading of the existing network leads the system to power loss in some of the feeders, minimizes the efficiency of the system, reduces voltage profile, and minimizes the reliability of the system.

Due to the spread of commercial and industrial transformation in the area, the performance of the Sebbata-I distribution substation network is not as efficient as the international distribution network. There is a problem with a power interruption frequently, fluctuation of voltage/under voltage, voltage imbalance, and operating with a weak power factor as tried to observe from the control room and recording data of that substation. These all problems can be resolved by optimally placed the appropriate custom power devices technology which compensates the adequate reactive power to the feeder for reducing the power loss and improving voltage profile. In order to reduce power losses and enhance the voltage across buses, reactive compensating devices are required in the distribution system.

There is various power electronics-based device that can control the power system by providing reactive power to the system. Series voltage regulators and shunt capacitors are also used to compensate for power losses reduction and keep voltages within limits, but these two devices have some drawbacks. For example, series voltage regulators operate in a step-by-step mode, which results in slow response and the inability to generate reactive power. To compensate for these limitations, shunt capacitors cannot generate continuous reactive

power. Custom power devices/D-FACTS are employed in power systems to improve power flow capability by controlling voltage, current, and phase angle parameters. Custom power devices, which are closely related to FACTS devices, are used to overcome issues in the power system network such as power interruption and power quality. In the transmission system, FACTS devices are employed, whereas custom power devices are applicable in the distribution network. Custom power devices are especially effective in system reliability and power quality issues[3][4].

Integration of compensating pieces of the device should be substantial to improve the performance of the distribution system by reducing power loss, enhancing voltage profile, voltage stability margin, cost of energy savings, improving reliability and security of the system. So, we need to use highly advanced equipment for the power quality problem of the distribution network. The majority of compensating devices used in the radial distribution network are capacitor banks, shunt and series reactors, automatic voltage restorer(AVR) and The different recently developed distribution network D-FACTS devices are also used in the power distribution system to minimize power quality problems, these include; static var compensator(SVC), thyristor controlled series compensator(TCSC), Unified power flow controller(UPFC), interline power flow controller(IPFC), and Distributed Static Compensator(DSTATCOM). DSTATCOM is made up of a shunt-connected voltage source converter that can compensate the bus voltage for better power factor and reactive power mitigation in the RDS. Low losses, less harmonic generation, compact size, and low cost distinguish D-STATCOMs from other compensating devices. Furthermore, they will not cause any operational issues such as resonance or harmonics[1][3].

The appropriate sizing and placement of D-FACTS devices are required to achieve the desired performance in the device resources, such as lowering power losses, increasing the voltage profile, voltage stability, maximum load ability, power factor improvement, and reactive power mitigation of the electric grid. Different optimization approaches have been suggested by various researchers to optimally size and allocate the device in the distribution network to improve its performance through fixing power quality issues. In the distribution network, there are two ways for sitting and sizing DFACTs devices. The first way is based on traditional methods such as optimal power flow (OPF), sensitivity factor, and repetitive load flows. In the second method, artificial intelligence (AI) algorithms such as Ant Colony Algorithm (ACO), Ant Lion Optimization Algorithm (ALOA), Genetic Algorithm (GA), Harmony Search (HSOA), Tabu Search (TS), Bat Algorithm(BA), Teaching and Learning

Process (TLPOA), Bacterial Foraging Optimization Algorithm(BFOA), Differential Evolution (DE), and Particle Swarm Optimization(PSO) are utilized to size and placement of D-FACTS devices. PSO is the most extensively used algorithm among those described above due to features such as ease of development, minimal computing load, and fast convergence. PSO is useful for a wide range of problems for which precise mathematical models are difficult to come by. The PSO algorithm, on the other hand, is prone to relapsing into local minima and premature convergence when addressing complex optimization procedures[5].

In this thesis work, the particle swarm optimization algorithm has been used with the MATLAB program to determine the appropriate size and placement of DSTATCOM, while the suitable candidate bus for DSTATCOM placement has been determined by voltage sensitivity index, with insertion of DSTATCOM at each bus with the corresponding size found by considering total loss reduction and voltage profile enhancement. The forward-backward load flow method has been used for the power flow analysis of the system in the MATLAB program. The DSTATCOM is regarded to be installed in the primary distribution system, to reduce overall active and reactive losses and increase the voltage profile, and voltage stability of the distribution network.

1.2 Statement of the Problem

Electricity is critical to any country's industrial, commercial, and socio-economic development. The generation station generates electricity, which is then transported to the load centers via transmission lines. A distribution system is the end part of a power system that distributes medium and low-voltage electric power to customers. Distribution networks are substantially known for their vulnerability to power quality problems that could bring on the inability to distribute the same amount of power generated at the load demand.

Sabbata one substation has been selected as a case study in this thesis work. The Sabbata-I substation is allocated at the western side of Addis Ababa, the capital city of Ethiopia where most of the electric power generated is consumed for the reason that various residential, commercial, and industrial centers are located around there. The substation has fifteen distribution feeders that supply electricity to various parts of Addis Ababa and the Oromia special zone Sabbata.

The electrical load demand on the Sebbata-I distribution network has been steadily expanding as a result of commercial, an ever-growing residential, and the building of various

industrial parks. The increasing load demand on the distribution network makes the system component overloaded which causes interruption of power, losses, voltage instability, working in weak voltage levels, voltage drops. Due to the overloading of the existing system, the outgoing feeder of the Sebbata-I substation now experiences frequent power interruptions, resulting in power loss and operation of some bus voltage levels near the allowable voltage limit. This problem was identified by observing the current distribution system status from the control room and the recorded data. The thesis work has been focus on one of the Sabbata–I substation's outgoing feeders, which experiences occasional power outages due to overloading.

Hence, the outgoing feeder-12 of the Sebbata-I substation has been chosen as a case study. To address the issues, a suitable solution was implemented on Ethiopia's Sebata-I substation's outgoing feeder-12. As a result, employing the PSO algorithm to integrate Distribution Static Compensator to the selected feeder in the optimum location and size has been played a vital role in resolving the identified problem.

1.3 Objectives

1.3.1 General Objective

The overall goal of the thesis work was to reduce power losses, enhance voltage profile and voltage stability of radial distribution network by optimal size and placement of distribution static compensator using particle swarm optimization algorithm.

1.3.2 Specific Objectives

The following are some of the specific objectives of the thesis.

- ✓ To collect the data of Sebbata-1 distribution Substation.
- ✓ To evaluate the performance of the selected feeder using forward/backward Sweep.
- ✓ To determine the optimal size, and location of the D-STATCOM using PSO.
- ✓ To analyze the performance of the feeder with and without DSTATCOM integration.
- ✓ To evaluate the cost-effectiveness of the system on a distribution system.
- ✓ To draw a conclusion and recommendation based on the obtained result.

1.4 Scope and Limitation of the Thesis

The thesis work is limited to the Sebbata-I substation at Sabbata-12 outgoing feeder. This thesis focuses on using a particle swarm optimization algorithm to determine the optimal size and placement of the Distribution Static Compensator on the radial distribution network to evaluate its impact on power loss reduction and bus voltage profile improvement under

steady-state operating conditions. The impacts of the device under a dynamic operating state doesn't been examined in the thesis. The phase imbalance and harmonics effect doesn't consider in this thesis. The implementation of the thesis work has been limited to computer simulation.

1.5 Significance of the Study

The thesis work will provide a solution for improving power system performance in order to meet load demand and deliver sustainable electric power. It improves the network capability of distribution systems and allows extra loads to be added without overloading the system. It maintains voltage profiles, voltage stability margin and improves system parameters within allowed limits, and also postponing the cost of replacing distribution feeders. The study confirms that custom power devices are an effective method for enhancing distribution system performance by reducing system losses and increasing bus voltage level and voltage stability.

1.6 The Organization of the Thesis

The content of this thesis work is organized into five chapters which are arranged as follows **The first chapter** presents the overall introduction of the thesis work which clarifies the basic concept of the thesis and gives the direction to the body of the thesis. **The second chapter** states the theoretical background of the distribution system, the method of improving the distribution system performance, and the overview of FACTS devices. It contains a literature study based on the preceding findings, which are related to the distribution system's power quality problem, particularly power loss reduction and improving the voltage profile of the distribution line. **Chapter three** deals with the description of the case study area, the required data and analyzing the collected data and also discussing the optimization techniques. The simulation results, and discussion for optimal size and allocation of distribution static compensator on Sabbata-I substation, feeder-12 in two instances, namely with and without installation of DSTATCOM, presented in **Chapter four**, along with a cost-benefit analysis. The conclusion and recommendations of the thesis work were discussed in **Chapter five**.

CHAPTER TWO

BASIC THEORIES AND LITERATURE REVIEW

2.1 Electrical Power Distribution System

An electric power system is made up of three primary components including generation, transmission, and distribution systems. Power plants are strategically located, often away from customers, to generate electricity. Transmission lines, which are conductors, are then used to transport them over long distances to load centers. Finally, it is distributed to a massive number of small and large consumers through a distribution network. The medium voltage is delivered to distribution transformers near the customer's location via primary distribution lines. Distribution transformers reduce the voltage to a level suitable for domestic appliances, which is then fed to a large number of consumers via secondary distribution lines.

Finally, a distribution network is used to reach out to a wide range of small and large customers. To provide electricity to all of the individual customers, distribution networks are usually installed in every part of every town and village. The distribution system must be able to satisfy the specific needs of individual consumers, such as energy demand, efficiency, and power quality. Feeders, distributors, and service mains are the most common components[6]. A single diagram of the distribution system is shown in Figure 2.1 below.

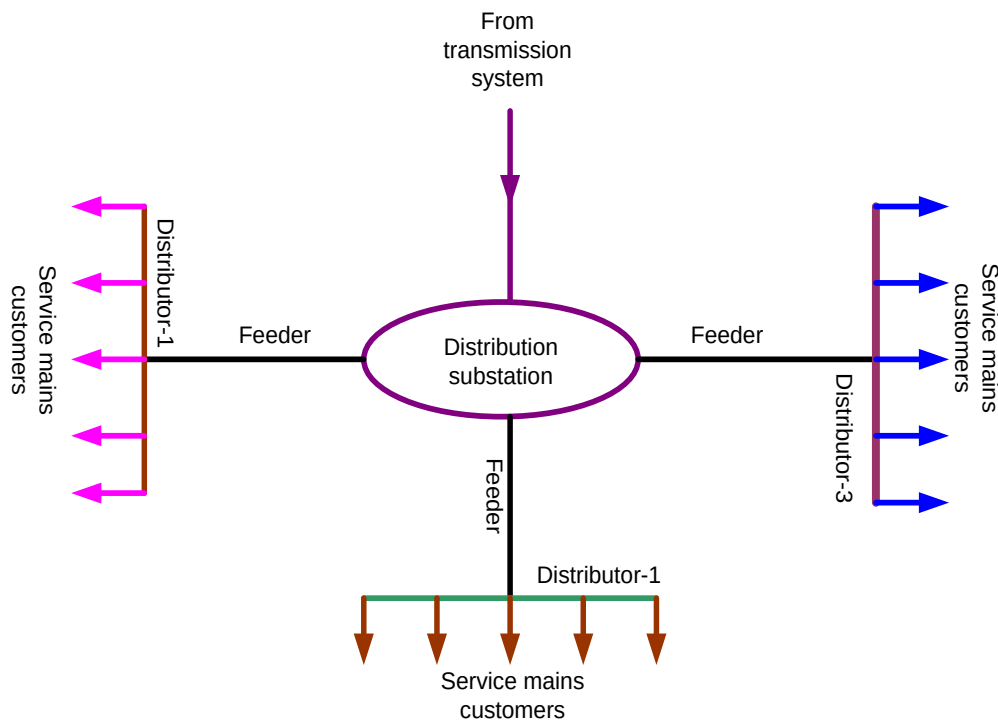


Figure 2.1 Single line diagram of a typical low-tension distribution system

A **feeder** is a conductor that runs from a substation (or localized generating station) to the region where power will be transmitted. In most cases, no tapping is taken from the feeder, ensuring that the current in it stays constant. The current carrying capacity is the most important factor to consider when designing a feeder.

A **distributor** is a conductor from which taps for supply to customers are taken. The distributors are shown in Figure 2.1 as distributor-1, distributor-2, and distributor-3. Since tapping occurs at different points along the length of a distributor, the current flowing through it is not constant. The key concern when designing a distributor is voltage drop along with its range since the allowable limit for voltage variations at the consumer's terminals is $\pm 6\%$ of the rated value. In most cases, a **service main** is a narrow pipe. The cable connects the distributor to the terminals of the consumer[7].

2.1.1 Categories of Distribution System

A distribution system may be classified based on the following factors:

Depending on the nature of the current, it can be classified as AC or DC distribution system. Based on the type of construction, the distribution system is classified as an Overhead or Underground system. A distribution system can be classified as a radial distribution network, a ring main system, or an interconnected system based on its operation scheme[7].

2.1.1.1 Radial Delivery System

The radial distribution system is made up of separate feeders that run from a single substation and supply the distributors at only one end. The root node sends power to the sub-branches, which are subsequently separated at the line. There are no loops in the network because of the radial layout, and each bus has just one path to the source. It is the most cost-effective network configuration, but it is also the least secure. In sparsely populated areas, the radial distribution method is commonly used. In this system, separate feeders spread from a single substation and supply the distributors from just one end. Figures 2.2 depict a single line diagram of a radial structure for the distributions system. The shortest delivery circuit with the lowest initial cost is this one[8].

The following are the characteristics of the radial distribution system:

- Radial networks (power sources supplied at one side only)
- Low X/R ratios, due to high resistance and low reactance of the line
- The unbalanced operation, distributed load and multi-phase
- Distributed generation is difficult to dispatch.
- Less expensive but least reliable network configuration.

- Because of these characteristics, radial distribution networks are referred to as ill-conditioned systems, making traditional power flow analysis difficult[9].

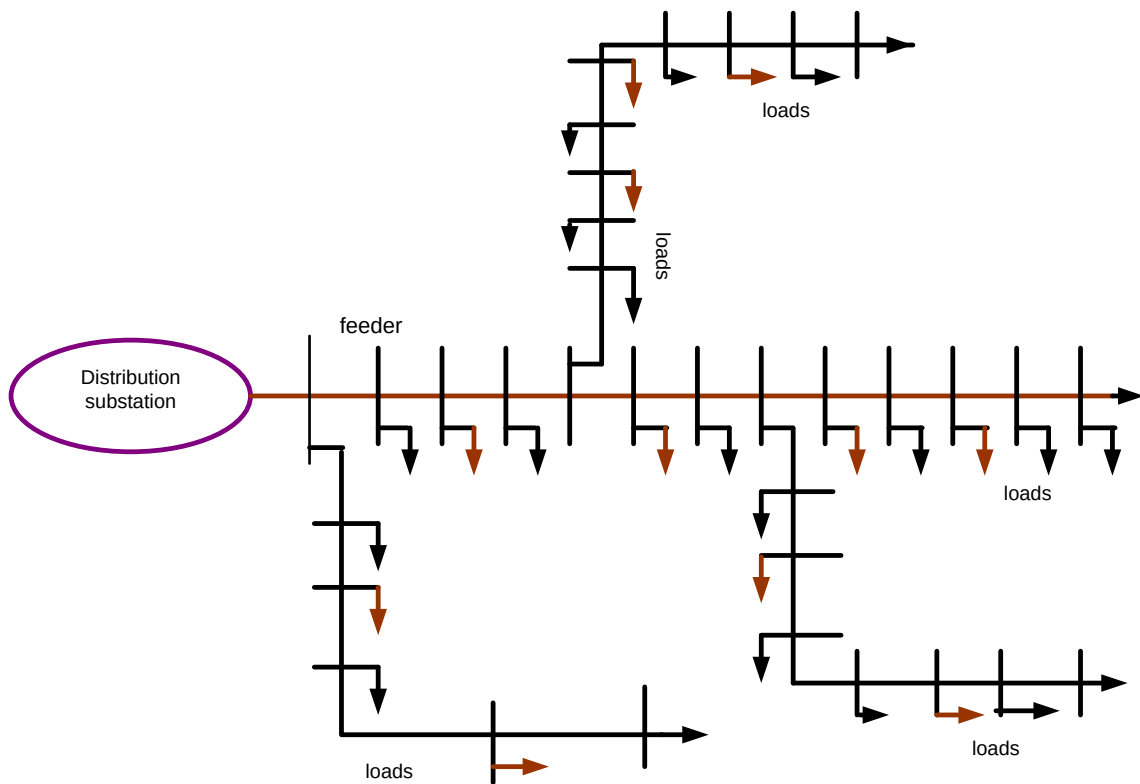


Figure 2.2 Radial distribution systems

However, it does have the following weaknesses:

- The end of the distributors closest to the feeder point will be heavily loaded.
- Customers can only deal with one feeder and one distributor. As a result, any fault in the feeder causes service to be interrupted for customers on the fault's side.
- Customers at the far end of the distribution will experience large voltage changes if the load on the distributor increases.

2.1.1.2 Loop System

In this arrangement, the primaries of distribution transformers create a loop. The loop circuit begins at the bus bars of the substation and rings through the service area before returning to the substation. Figure 2.3 represents a single line diagram of an a.c. distribution ring main structure with substation supplies to the closed feeder LMNOPQRS. The distributors are tapped from separate places M, O, and Q of the feeder via distribution transformers. The ring main system is often more expensive than the radial system since it requires more switches and conductors. The cost of construction is high and the radial distribution system method is preferable rather than the ring system due to the above reasons.

The ring distribution system has the following advantages:

- At the consumer's terminals, there are fewer voltage fluctuations.
- The system is particularly reliable because each distributor is fed by two feeders. The supply is preserved in the event of a fault on any part of the feeder. Assume that the fault occurs at every stage F of the feeder's segment SLM. The feeder's segment SLM can then be separated for repairs while the feeder SRQPONM maintains supply to all customers.

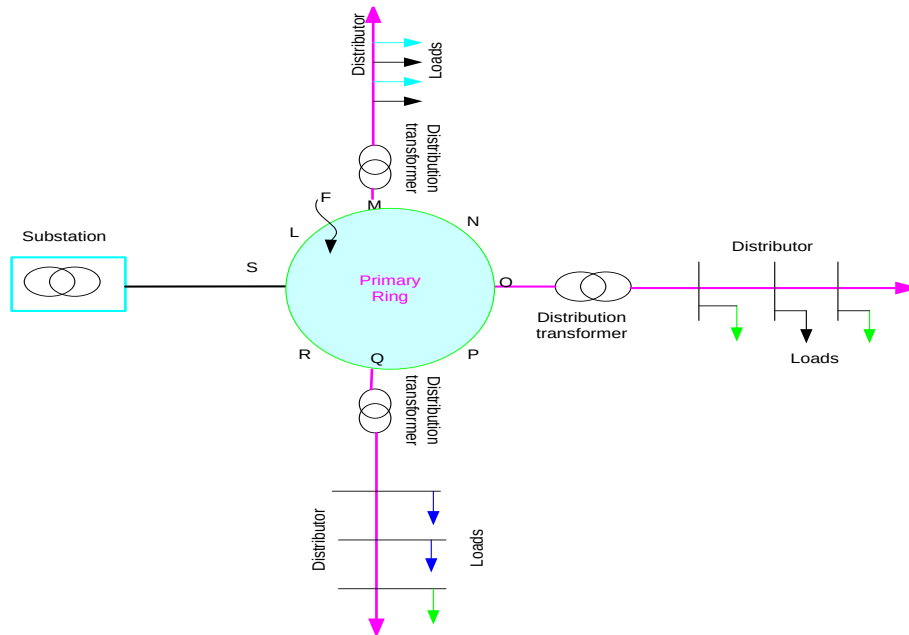


Figure 2.3 Ring main systems

2.1.1.3 Inter-Connected System

An interconnected distribution system refers to a feeder ring that is energized by two or more generating stations or substations. Figure 2.4 shows a single line diagram of an interconnected loop with two substations S_1 and S_2 at points D and C, respectively, supplying the closed feeder ring ABCD. Distribution transformers bind distributors to the feeder ring's points O, P, Q, and R.

The following are some of the benefits of an interconnected system:

- It improves the service's dependability
- Service reliability increases
- Good voltage regulation is achievable
- During peak load hours, any area fed by one generating station can be fed by the other generating station. This decreases reserve power capability and improves system reliability.

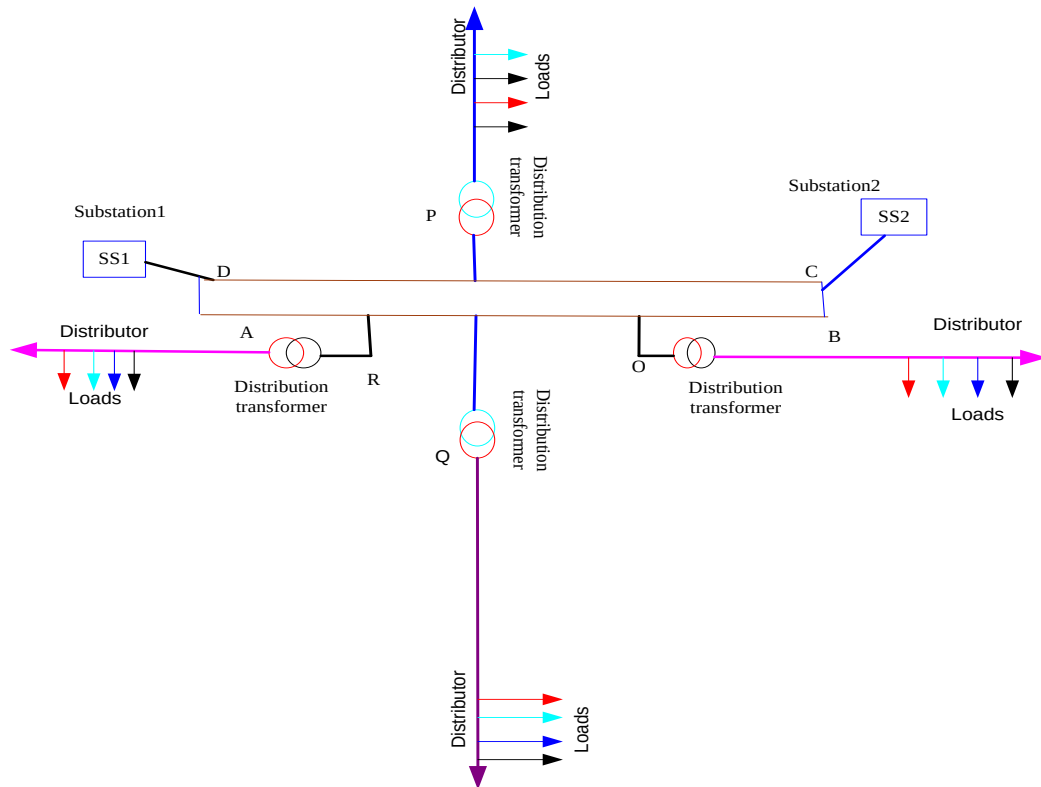


Figure 2.4 Interconnected distribution system

2.1.2 Requirements of a Distribution System

Maintaining a reliable electric power supply that fulfills the needs of all types of consumers takes a lot of work. Some of the characteristics of a successful distribution system requirement include proper voltage, availability of power on demand, and reliability[7].

a) Appropriate Voltage

A voltage profile can be used to define the variance in node voltages concerning the source (rated) voltage across the entire network. Voltage instabilities at end-user terminals should be as minimal as possible, which is a significant requirement of a distribution network. Variations in voltage are typically caused by changes in the load demand on the system. Low voltage results in high loss, inefficient lighting, and the possibility of motor burnout. High voltage can cause lamps to burn out permanently and other appliances to malfunction. As a result, a good distribution system can keep voltage variations at user terminals within acceptable bounds.

b) Availability of Power on Demand

Power must be available to the consumers in any amount that they might need from time to time. For example, Motors may be started or stopped, and lights may be turned on or off without prior notification to the electric utility. since electricity cannot be stored, the

distribution system must be able to satisfy the demands of the users. This implies that operating employees monitor load patterns regularly to predict large load fluctuations that occur according to predetermined schedules.

c) Reliability

Reliability means if there is a power failure it should be for the minimum possible time. The activity of modern manufacturing is almost entirely dependent on electric power. Electric power is used to illuminate, cook, cool, and ventilate homes and office buildings. Electric power, like anything else created by humans, can never be completely reliable. However, there is a lot that can be done to increase reliability. Reliability could be improved by a control system that is automated and made a greater number of reserve facilities available.

2.1.3 Distribution System Power Loss and Voltage Drop

The distribution system sector needs an economical system to deliver electrical energy at a reasonable price, with minimal voltage drop and low power loss but, electrical power distribution networks have both technical and non-technical losses. The technical losses are related to the energy distribution process, which occurs due to the physical design of the power system's equipment and facilities, such as copper loss in the conductor, transformer, switches, and generators. The non-technical losses stem from the customer service process, which includes incorrect meter activity and illegal use in coordination with utility employees. The voltage drop and power loss are caused by the distribution overhead lines' resistance and reactance. Although it is difficult to fully eliminate power loss and voltage drop, these issues can be minimized by employing techniques such as capacitor integration, network reconfiguration, DG insertion, and FACTS devices.

2.1.4 Type of Losses in Distribution System

We are aware that certain losses affect the power system economy. It is common knowledge that not all of the energy delivered to a distribution system reaches the end-user. Technical and non-technical losses in distribution systems waste a significant amount of energy. In the power sector, the distribution system accounts for the majority of technical and non-technical losses [10].

2.1.4.1 Technical Losses

The physical properties of the apparatuses of the power system cause technical losses in the power system. The power lost in transmission lines and transformers due to internal electrical resistance is the most obvious example. Technical losses are losses that occur naturally (as a result of internal power system action) and are primarily caused by power dissipation in

electrical system components such as transmission lines, power transformers, measurement systems, and so on. If the power system in question contains known quantities of loads, technical losses may be computed and regulated. Technical losses that occur during transmission and distribution include a substation, transformer, and feeder losses. These include main feeder resistive losses, distribution transformer losses (resistive losses in windings and core losses), secondary network resistive losses, service drop resistive losses, and kWh meter losses.

Electricity distribution has fundamental losses that cannot be avoided. Technical losses are caused by current flowing through an electrical network and include the following losses:

Copper losses are caused by I^2R losses, which are inherent in all inductors due to conductors' finite resistance. **Dielectric losses** are caused by the heating of the dielectric material that separates conductors and **Losses caused by induction and radiation** that losses are caused by the electromagnetic fields that surround conductors. Technical losses can be computed and regulated if the power system in question contains known quantities of loads.

Technical losses are caused by the following factors as disturbance of harmonics, improper earthing on the part of the consumer, single-phase long lines, improper loading, overloading and low voltage, losses as a result of substandard equipment.

2.1.4.2 Non-Technical Losses

Non-Technical losses, on the other hand, are those caused by events outside of the power system or by loads and conditions that the technical losses calculation overlooked. Non-technical losses are more difficult to assess since they are frequently ignored by device operators and lack recorded data. On the other hand, non-technical losses (NTL) occur as a result of energy theft, metering inaccuracies, unmetered electricity, faulty energy meters, profiling error, ignoring overdue bills, an unpaid bill, Pressuring meter readers to take false readings, and dismiss past-due bills and Stealing by bypassing the meter or making other illicit connections[11][12]. Different approaches for the efficient handling of NTLs in energy distribution systems have been presented as a result of the NTL challenges faced by power providers. Smart electronic meters are now the most effective approach for reducing NTLs. However, while their installation is advantageous, the cost is significant, and new infrastructure for data collection is necessary[13].

Both primary and secondary feeders may experience line losses in the distribution system. The square of the current flowing through the resistance (R) and reactance (X) of the line determines the line losses. The next formula can be used to calculate line losses:

$$P_{loss} = \sum_{i,j=1}^N (i_{ij}^2 R_{ij}) \quad (2.1)$$

$$Q_{loss} = \sum_{i,j=1}^N (i_{ij}^2 X_{ij}) \quad (2.2)$$

Where: P_{loss} = total active power loss; Q_{loss} = total reactive power loss; i_{ij} = branch current flowing from bus i to bus j; R_{ij} = line resistance between bus i and bus j; X_{ij} = line reactance between bus i and bus j.

❖ Impacts of Non-Technical losses on Distribution System

The effects of non-technical losses are mainly reflected in the following aspects[14]

- ✓ Lead to over-voltage, affecting performance or even damage to equipment
- ✓ large amount of non-technical damage may result in tripping, resulting in disruption to the customer's power supply.
- ✓ The unpredictable additional load caused by NTLs may result in power outages and blackouts during the peak period.
- ✓ In the energy sector, the NTL has caused massive economic losses to power providers, forcing the surviving utility firms to recover the expenses by imposing excessive charges on all customers, which is extremely unfair to honest customers.
- ✓ Illegal electricity theft also easily leads to security risks.
- ✓ Improper operation of distribution feeders may put the entire community at risk because these wires may spark and cause a fire in extreme weather conditions.

2.1.5 Voltage Drop in a Distribution System

In an ideal condition, the receiving end voltage and the sending end voltage should be the same in any power transfer system, whether a transmission line or an electric circuit. However, the receiving end voltage is not the same as the transmitting end voltage under normal circuit conditions. This is due to voltage drops along the line which are caused by the combined effects of resistance and impedance of the conducting instruments. A voltage drop arises due to the resistance and reactance of a distribution system. In addition to the non-technical losses already listed, there are overhead line losses. Even though all equipment connected to the utility system is designed to be used in a specific way, it is virtually impossible to service every customer exactly to the same voltage. Since voltage drops occur in any part of the power system, nameplate voltage is used from the generator to the meter of the customer[6]. Figure 3.5 depicts a simple description of voltage drop in a distribution system.

The load complex apparent power as a function of current I

$$S = P_L + jQ_L \quad (2.3)$$

and the load voltage V_2 will be

$$I = \left[\frac{S}{V_2} \right] = \frac{P_L + jQ_L}{V_2} \quad (2.4)$$

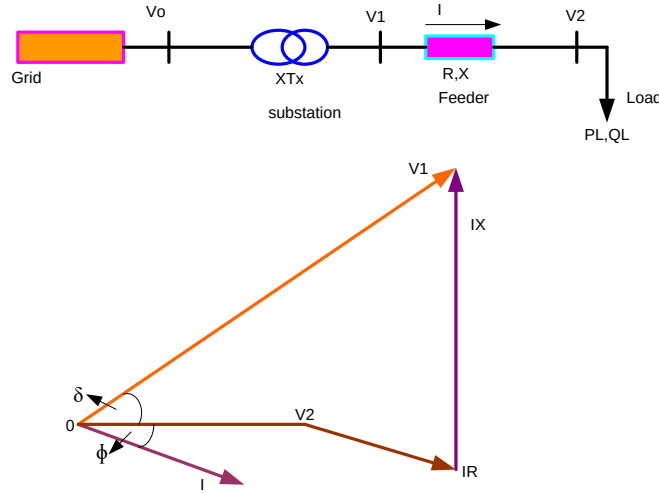


Figure 2.5 One-line diagram and corresponding phasor diagram for an illustration of the voltage drop in a distribution system

The voltage drop on the feeder is calculated as follows:

$$V_1 - V_2 = I(R + jX) = IR\cos\theta + IX\sin\theta = RP_L + XQ_L - \frac{j(XP_L - RQ_L)}{V_2} \quad (2.5)$$

For small power flow, the voltage angle θ between V_2 and V_1 in the above equation is small and the voltage drop $\Delta V = |V_1 - V_2|$ can be approximated by

$$\Delta V \cong \frac{RP_L + jXQ_L}{V_2} \quad (2.6)$$

Where I : is Current through the feeder; θ : is Power-factor angle; R : is Resistance of the feeder; X : is Reactance of the feeder; V_1 : is sending end voltage; V_2 : is receiving end voltage; P_L : is active load power; Q_L : is reactive load power; ΔV : is the voltage drop. Equations (2.5) - (2.6) show that the load often induces a voltage drop and that the voltage profile of traditional distribution systems decreases at the end. Voltage control in distribution systems is based on voltage drops and voltage profiles[15].

2.1.5.1 Factors Affecting Voltage Drop in Distribution System

Due to a variety of reasons, voltage variance and distribution feeder loss are rising in the distribution network. the voltage drop of a line depends mainly on two factors; this being the line impedance and the current flowing through the conductor. Therefore, an increase in

either impedance or current will cause a corresponding increase in a voltage drop[16]. The following are a list of some of the factor affecting voltage drop[17].

Poor jointing and termination: Because of the poor jointing and termination on distribution networks caused by loose contact, there will be a lot of resistance to current flow, which will generate heat. This causes a rise in resistance and, as a result, a voltage drops at that location.

Conductors that are too small: Voltage can be thought of as the force that pushes charges along a conductor, while conductor resistance is a measure of how difficult it is to push the charges along. Small size conductors have high resistance, resulting in a significant voltage drop.

Using different sorts of conductor materials: When selecting conductor materials, corrosion is an important consideration. Oxidation and galvanic corrosion are the two forms of corrosion that have the most impact on a metal's electrical properties. Galvanic corrosion is a form of corrosion caused by an electrical potential difference between two or more metals, has to be given careful consideration when selecting conductor materials.

Hot spots: A high resistance point is produced whenever a mechanical joint or termination is made. As a result, the joint or termination will gradually fail. High resistance causes localized heating, which accelerates oxidation and creep, causing the connection to loosen and further heating until the contact glows.

The main feeder loads: The main reason for voltage decreases on the feeder is an increase in current due to the feeder being overloaded. The loads connected to the downstream portion of the feeder determine the currents in a feeder section along the distribution feeder. The current does not affect the feeder impedance, but it does affect voltage deviation.

Distribution feeder length: The length of a feeder's series impedance is linearly proportional to the feeder's length. As a result, the length of the feeder has a large impact on voltage variance.

Unbalanced phase: A network with unbalanced load distribution through all three phases would have higher currents in at least one phase, indicating that it is not designed to minimize losses [18]. If neutral conductors are present, currents can pass through them as well. As a result of the quadratic relationship between losses and current, this load imbalance over the three phases would result in increased losses

Harmonics: Harmonic effects are AC profile distortions. Because the AC magnetizing current is not perfectly sinusoidal, it can occur in transformer windings. This, however, is more common on the triple harmonics (3rd,6th,9th). As a consequence, on a typical three-phase device, they are all in phase and produce no real harmonics. Harmonics generated by

other network equipment, on the other hand, will not cancel in the neutral conductor. As a result, the distribution system could suffer additional losses.

Power factor: The ratio of actual power to apparent power is known as the power factor. When two power factor systems deliver the same amount of real power, the system with the lower power factor would have a higher reactive power current, resulting in a higher voltage drop and higher loss.

The substation transformer's rated capacity: By the rated capacity of their feeding substation transformer, the variance of node voltage along the feeder can be reduced. The greater the transformer power, the lower the impact of voltage variance on the device. However, an increase in the short-circuit fault current level on the secondary side of a substation transformer is one of the main drawbacks of increasing the rated capacity of a substation transformer.

Distribution transformer's location: Inadequate distribution transformer placement can result in energy loss in the distribution system. In comparison to the consumer closest to the distribution transformer, the farthest consumer would receive an exceptionally low voltage. The following are the consequences of a voltage drop on the end-user.

- Lighting illumination has a negative impact.
- Equipment life expectancy is being shortened.
- Utility costs have risen.
- Inadequate operation

Various factors affect the power system to reduce the power quality of the system, however, distribution system planning objectives are as follows to supply the end-user:

- ✚ Meeting the load growth at the desired quality.
- ✚ Providing efficient and reliable supply.
- ✚ Maximizing the performance of system components
- ✚ Satisfying the most cost-effective means of DS development and
- ✚ Minimizing the price of electricity to customers by choosing the most cost-effective solution and minimizing total life cycle costs.

Therefore, the distribution system planning is based on the following key aspects including load forecasting, power quality, compliance with standards, investment with the highest revenue, power loss, and amount of loss of load [19].

2.1.6 Techniques for Improving Distribution Systems Performance

A variety of techniques can be used to reduce the loss and voltage variation of a distribution feeder[20]. Some of the power loss and voltage drop reduction techniques include network reconfiguration, network re-conducting (conductor grading), distribution transformer locating and sizing, reactive power compensation, highly effective transformers, high voltage distribution systems, distributed generation, and building new substations. The techniques for lowering power loss and voltage drop are explained as follows.

A) Network Reconfiguration

Network reconfiguration is the process of operating switches to adjust the circuit topology to minimize operating costs while meeting defined constraints. Network reconfiguration, in which the power flow is altered by making new ties with a feeder to create a tree structure or by opening or closing the appropriate switches on the feeder, is one way of minimizing loss in a distribution system. Loads can be altered from heavily loaded feeders to lighter-lighter feeders, as well as from higher-resistance routs to lower-resistance routs, where the resistance route is the entire resistance from the supplier to the end-user, to obtain the lowest loss. These transfers are effective not only in cutting losses and reducing the number of loads on the switched feeder but also in improving the voltage profile of the feeders and lowering total system power losses[21][22].

Feeder reconfiguration, on the other hand, can be advantageous if the distribution feeders are automated and not too far apart. Feeder reconfiguration for automatic and widely apart feeders may not be cost-effective.

B) Making Use of Distributed Generation

The opinion of distributed generation (DG), which dates back to the early 1900s, is focused on small-scale power plants linked to the electricity grid near customers [23]. Small-scale power generation that is normally connected to a distribution grid is known as distributed generation (DG). DG is described by the Electric Power Research Institute (EPRI) as generation ranging from a few kilowatts to 50 megawatts. The most recent concept of DG, according to Ackermann et al., is "an electric generation source linked directly to the distribution network on the customer side of the meter"[24].

C) Reactive Power Compensation

Voltage profile variation, increased power flow capacity (by reducing feeder impedance), increased system capacity (by regulating reactive power flow with capacitors), and reduced power losses are all advantages of reactive power compensation in the transmission and distribution system [25]. In general, reactive power compensation is an effective method for

improving a distribution network's voltage profile and loss if the size and position are optimized. This can be accomplished by installing various reactive compensation equipment.

D) Conductor Grading

Conductor grading is a technique for reducing resistance by replacing the current conductor on the feeder with a conductor of appropriate size for optimal (cost) feeder length. This can be accomplished by replacing the small size conductors with a larger cross-sectional area, or by adding auxiliary conductors to operate in parallel with the current ones. As a result, the equivalent resistance is lower. While these methods can result in significant energy savings, they are not cost-efficient and are only used where there is a specific need. The cost of conductors and their installation is generally greater than the cost of the energy saved.

This technique is used when an existing conductor is no longer adequate due to rapid load growth. This technique is also useful in developing countries where annual population (energy demand) growth rates are high and conductors are selected to reduce power loss and voltage drop in the distribution system.

E) Locating and Sizing Distribution Transformers

Even if the secondary of the transformer is maintained at a tolerable voltage level, if distribution transformers are not positioned centrally concerning customers, the farthest consumers will receive severely low voltage. As a result, there are more losses in the distribution system. As a result, distribution transformers should be placed as close to the load center as possible, and large transformers should be replaced with transformers of limited rating that serve a small number of customers to maintain an optimal voltage level.

F) Making Use of High-Efficiency Transformers

The use of high-efficiency transformers would lower distribution system losses. Amorphous core transformers, for example, have a high magnetic susceptibility as well as a high electrical resistance. Eddy current losses are minimal in transformers due to their high resistance.

G) Make use of a high-voltage power distribution system

The loss and voltage deviation of the distribution system would be reduced by using a high voltage distribution system. This method entails bringing high-voltage lines as close as possible to the load and replacing large transformers with a variety of small-rating transformers. Also, conversion of existing low voltage distribution systems to high voltage distribution systems is done. This method is more reliable and powerful for lowering technical losses and improving power quality in distribution systems. Since the current in a

high-voltage device is very low. However, the initial investment is so large, it might not be feasible.

2.1.7 Overview of Flexible AC Transmission System Devices

Alternating current transmission systems with power electronic-based and other static controllers to improve controllability and power transfer capability are known as Flexible AC Transmission Systems (FACTS). It controls one or more AC transmission system parameters using an electronic-based system and other static equipment. A flexible AC transmission system device can make the power system more controllable and safe. Controlling the parameters of a power transmission system can increase system stability and power transmission capacity, as well as improve power flow, and reduce transmission loss. Reactive compensation devices are typically used to supply or absorb reactive power, allowing the reactive power balance to be regulated in the desired manner. FACTS devices are used for a variety of purposes, including power flow control, increased transmission capability, voltage control, reactive power compensation, stability improvement, power quality improvement, power conditioning, flicker mitigation, and interconnection of renewable and distributed generation and storage [26][27].

FACT's device can be Thyristor based such as Static VAR-compensator, Thyristor Controlled Series Compensator (TCSC), and voltage source converter based such as Static Synchronous Series Compensator (SSSC), Static Synchronous Compensator (STATCOM), Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC)[28].

The power electronic-based controllers are the main devices in the application, as can be seen from the above descriptions. It also contains certain non-power electronics static controllers, such as the MSC/MSR (Multiphase Switched Capacitor/Reactor). FACTS controllers can be classified into four groups based on how they are related to the power system, these are FACTS Controllers in a series, FACTS controllers in a Shunt, FACTS Controllers in Series-Series Combination, FACTS Controllers with a Series-Shunt Combination [29][30].

2.1.7.1 FACTS Controllers in a Series

These FACTS Controllers may be variable impedance sources like capacitors, reactors, or power electronics. Typical series compensators use capacitors to lower the equivalent reactance of a power line at rated frequency, increasing the voltage at the load terminals and injecting voltage in series with the line. The series controllers only supply or consume variable reactive power since the voltage is in phase quadrature with the line current. Any

other step relationship would entail dealing with real power. The various important series compensator is Static Synchronous Series Compensator (SSSC), Thyristor-Controlled Series Compensation (TCSC), Thyristor Controlled Series Capacitor (TCSC), Thyristor Switched Series Capacitor (TSSC), and Static Synchronous Series Compensators(SSSC).

2.1.7.2 FACTS Controllers in a Shunt

Shunt Controllers are variable impedance sources, such as capacitors, reactors, and power electronics, that are shunt connected to the line to inject variable current. The shunt Controllers only supply or consume variable reactive power as long as the injected current is in phase quadrature with the line voltage. Any other step relationship would entail dealing with real power. The important shunt compensators are Static-VAr Compensator (SVC), Static Synchronous Generator (SSG), Thyristor Controlled Reactor (TCR), and Static Synchronous Compensator (STATCOM). The following are the goals of a shunt compensator in the distribution system:

- To compensate for a low load power factor, the current drawn from the source would have a power factor of near unity. Harmonic suppression in loads, resulting in nearly sinusoidal current drawn from the source
- To control the voltage for loads that trigger supply voltage fluctuations.

2.1.7.3 FACTS Controllers in Series-Series Combination

These Controllers are made up of multiple Series FACTS Controllers that are operated in a multilane transmission system in a synchronized manner. FACTS Controllers with Combined Series-Series are set up to provide independent series reactive power compensation for each line while also transferring real power between lines via a power link. This configuration is known as "Unified Series-Series Controller" due to the existence of a power connection between series controllers. Interline Power Flow Controller is one of the series-series controllers (IPFC). It is used to control both real and reactive power flow in the lines, allowing the transmission system to operate at full efficiency.

2.1.7.4 FACTS Controllers with a Series-Shunt Combination

These are either a Unified Power Flow Controller with series and shunt components or a combination of separate shunt and series controllers that are operated in a coordinated manner. When the Shunt and Series FACTS Controllers are linked together, real power can be exchanged between the series and shunt controllers. Series-shunt controllers include the Thyristor Operated Phase Shifting Transformer (TCPST) and the Unified Power Flow Controller (UPFC).

2.1.8 Application of FACTS Devices

The application of FACTS controllers to the solution of the steady-state operating problem is outlined in table 2.1 below. It is important to note that within the power system, the above FACTS controllers allow transmission and distribution utilities to receive one or more of the following benefits on a case-by-case basis[31]:

Table 2.1 FACTS Controllers role in distribution system Operation

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

reactive power to prevent overload caused by high voltage following an outage, and finally supplying reactive power to prevent overload caused by low voltage following an outage can be done using FACTS controllers (STATCOM, SVC, and TCR)[33][34].

2.2 Literature Review

Many researchers are attempting to solve the power quality problem that occurs in power distribution networks by employing custom power devices such as AVR, UPFC, IPFQ, and DSTATCOM, as well as distributed generation, network reconfiguration, synchronous condenser, and capacitor banks. For the time being, the Sabbata-I distribution substation does not use any compensating devices that offer reactive power to compensate for significant voltage drop and power losses when the load demand varies. Therefore, this thesis work is interesting to study the Sabbata-I distribution network to improve the efficiency and quality of electric utilities. The literature on the integration of distributed static compensators on distribution networks is discussed as follows.

Salkuti(2021) proposed a method for allocating DG and D-STATCOM in the distribution network to enhance the voltage profile and reduce the radial distribution system's power loss. In this work, the metaheuristic/evolutionary-based algorithm is used to size the distributed generation and distributed static compensator in the radial distribution system. In this proposed work, two stability indexes are used to place the DG and D-STATCOM. Here, the loss sensitivity factor is employed to determine the optimal sitting of DG, while the voltage stability index is utilized for the optimal size of D-STATCOM. The proposed work is tested on two standard IEEE 34 and 85 bus radial distribution systems[35].

Balamurugan et al.(2018) state the way of improvement of distribution system performance by using optimal location and sizing of DSTATCOM with the aid of whale optimization algorithm. The objective function of the proposed work is the minimization of total power losses. The placement of DSTATCOM was obtained by voltage stability index. The whale optimization algorithm is utilized to obtain the optimal sizing of DSTATCOM. The proposed work is tested on Indian rural electrification 28-bus and standard IEEE 69-Bus radial distribution system[1].

Yuvaraj & Ravi(2018) describe a new mechanism based on bio-inspired Cuckoo Search Algorithm (CSA), which can importantly be imagined with the combination of placement of distributed generation and distribution static compensator in the radial distribution network. In the suggested procedure, voltage stability index and loss sensitivity factor are used to assign DG and DSTATCOM optimally. CSA in a radial distribution network is used to determine the optimum size of DG and DSTATCOM. The Backward/Forward sweep (BFS) algorithm is employed to calculate load flow in this article. The proposed method's primary goal is to minimize overall power losses while also improving bus voltages. The suggested

mechanism's effectiveness is evaluated using a well-known IEEE 33-bus and a massive 136-bus RDS[36].

Amin et al.(2019) in their paper proposed an efficient hybrid analytical coyote optimization algorithm to determine the optimal placement and sizing of D-STATCOM in the radial distribution system to minimize the active power loss and improve voltage profiles considering the operational constraints. The coyote optimization algorithm is utilized to determine the optimal allocation of D-STATCOM in the distribution system while the analytical techniques are used to determine the optimal size of DSTATCOM in RDS. The IEEE 33 and 69 bus system are utilized to validate the proposed work[37].

Salkuti(2019) Developed a new approach for optimal size and location of distributed generation and distributed static compensator in the radial distribution system for reducing the real power losses and voltage profile improvement. The author used different techniques in this work. Then the loss sensitivity factor is utilized to determine the optimal placement for DG whereas, the optimal sitting of D-STATCOM is determined by the voltage stability index. The optimal size of distributed generation and distributed static compensator are determined by the Artificial Fish Swarm Optimization Algorithm(AFSOA). The proposed work is tested on a standard IEEE 33 and 69 bus radial distribution system[38].

Iqbal et. (2018) introduce a system for minimization of losses and bus voltage enhancement inactive power distribution network by optimal placement of DG and D-STATCOM. On the MATLAB platform, the DLF mechanism is used for load flow calculation, and the loss sensitivity factor, along with under-voltage, is used as an objective function for optimal DG placement. This work has been put to the test on a 33-bus radial network[39].

Thangaraj & Kuppan(2017) present a new method for DG and D-STATCOM placement in the radial distribution network. The proposed work has a multi-objective feature that involves lowering power loss and total under-voltage while also increasing VSI within constraints. The lightning search algorithm was used to solve the multi-objective function (LSA). The user loads are changed linearly from light to heavy load with a 1% phase size in the proposed process. LSA evaluates the optimal DSTATCOM and DG sizing for each load phase. In different situations, the proposed approach is tested on two test systems of 33-bus and 69-bus[40].

G. Gowtham(2015) used fuzzy and PSO to minimize power losses and improve voltage profiles in distribution networks. The authors used the two proposed algorithms for optimal

D-STATCOM position and sizing, to reduce power losses and improve voltage profile. The proposed approach has been tested on bus systems 33 and 69. The four best placements are tested for power loss and voltages depending on priority. This paper also includes cases of 125 percent, 150 percent, and 175 percent overloading[41].

Kumarasundari(2019) identifies a mechanism for reducing losses and improving voltage profiles in an active radial distribution network. The optimal position of the DG is determined using the DLF method load flow and the loss sensitivity factor with voltage variance. DSTATCOM is strategically allocated in the network to keep up a stable bus voltage profile by supplying reactive power to the system network through DG. The proposed approach is validated using a MATLAB simulation of an IEEE 69-bus radial distribution network[42].

Arya et al.(2019) Proposed the way of optimally placing and sizing D-STATCOM in the distribution system to improve the distribution system performance. The main objective of the work is to system losses and enhancing the power quality of the system. The recently developed algorithm which is Gravitational Search Algorithm is employed to determine the optimal location of the devices for power loss reduction, improvement in voltage profile, and annual energy saving for the distribution operator. Load flow analysis is computed using a forward/backward algorithm. The proposed system is tested on IEEE 33 and IEEE 69 bus systems[43].

Yuvaraj et al.(2015) investigated the optimal placement and sizing of D-STATCOM using a harmony search algorithm. A single objective function that is called an optimization function is power loss minimization. The proposed work was put through its paces on the IEEE 33-bus system. For load flow analysis, it employs a direct BIBC matrix method. The proposed research compares RDS annual total loss before and after D-STATCOM installation. The actual and reactive power losses have both been reduced by 28.97 percent and 28.67 percent, respectively[44].

Rukmani et al.(2020) Suggested a new algorithm bio-inspired cuckoo search algorithm that can appropriately optimally allocate the D-STATCOM in a radial distribution system with the objective function of reducing total power loss and voltage profile improvement. In this work, the optimal location of the devices is calculated by loss sensitivity factor, while the optimal size of DSTATCOM finds using the proposed algorithm CSA. The load flow analysis is computed using the efficient approach backward/forward method[45].

According to the literature review above, it is possible to allocate and size DFACTS devices in the distribution network using an optimization algorithm, to reduce system losses and improve the voltage profile of the radial distribution network. The techniques proposed by different researchers have been centered on compensating devices using various optimization methods to solve the distribution network's power quality issue. However, the optimal placement and size of the device are one of the challenges of electric utility that can cause more power loss and poor voltage profile and some of the researchers have not been considered this factor when they give a solution to the problem. They didn't consider both real and reactive power, voltage stability, and voltage profile, and cost analysis at the same time. Some of the optimization algorithms that have been employed by the authors have a long simulation time, low convergence, which the above researchers did not consider when solving the problem. In addition to that, all authors have tested their methods on the IEEE distribution system i.e. their results are not applied to the real application of the distribution system.

In this thesis work, the device has been placed and size optimally using particle swarm optimization approaches. The real power loss, reactive power loss, voltage profile, voltage stability, and energy cost savings due to the integration of Distributed Static Compensator devices have been considered simultaneously. The multi-objective function, quick convergence characteristics of the particle swarm optimization algorithm and system constraints for PSO simulation have all been addressed in this study. The effective load flow analysis method (forward-backward sweep) which is more preferable for radial distribution systems and the voltage stability index that is used to select the candidate buses for DSTATCOM location has been used in this thesis work. The DSTATCOM that is highly impacting the distribution network has been used as a reactive power compensator. The thesis work focused on an active radial distribution network (sabbata-I substation distribution network) which provides electric power for the customers right now.

CHAPTER THREE

SYSTEM DESCRIPTIONS AND METHODOLOGY

3.1 Introduction.

In order to meet the thesis' objectives, different methods of collecting and analyzing data, as well as the methodology required to fix the problem identified on the select distribution feeder, are discussed in this chapter. The data collected during the two years (2019 and 2020) has been presented. These data include the cause of the interruption, duration of the interruption, frequency of interruption, length of the feeder, impedance (resistance and reactance) of each segment line, the active and reactive power on load point, peak, average, and minimum load of the feeder, each capacity of power and distribution transformer. The selected substation has fifteen outgoing feeders, regarding their problem, the feeder that has a more power quality problem than the others has been selected as a case study. This chapter also covers the load flow analysis method for evaluating the operating states of the existing system, as well as optimization approaches for locating and sizing the appropriate reactive power compensation device. Different equality and unequal constraints, problem formulation for objective function optimization method also discussed in this section.

3.2 Data Collection

The distribution system can be connected in radial and meshed forms, all Sabbata-I 15kV substation outgoing feeders are configured in radial form. some of the feeders are used to feed 60 to 80 distribution transformers. As the gap between the distribution transformer and the end consumer increases, the loss is increasing and voltage level is reduced further by distribution transformers to the minimum usage voltage of 380 volts three-phase or 220 volts single-phase.

To suggest a solution for the problem found in the case study area, Various data have been collected from different sources while doing the research work on Sabbata-I distribution substation 15kv outgoing feeder. The collected data categorizes into primary and secondary data. The important primary data specified to the selected distribution substation and its outgoing feeder have been gathered from various sections of Ethiopian electric power(EEP) and Ethiopian electric utility(EEU). The primary data has been collected by direct involvement, it includes direct observation of the Sabbata-I substation, switching sections, control room, loading of transformer and feeder, and also gathered through making an interview with operator of the substation. The primary data collected from the panel board

or control room by direct observations are the monthly peaks and minimum load of each feeder, monthly interruptions, and duration of interruptions with the cause of interruptions. The other data needed to accomplish this work has been gathered from the Ethiopian electric power engineering office, distribution design, and planning office, and Ethiopian Electric Utility, it includes the incoming power from the interconnected power system to Sabbata-I substation, distribution transformer main parameters, line data, the active and reactive power demand of the selected feeder at their bus terminals, conductor type and segment distance of the feeder.

Secondary data, on the other hand, is acquired from other researcher studies in the same or related problem areas. It involves examining documents and documentary reviews gathered from transmission line networks, as well as websites and other historical and documentary records pertinent to the study.

3.2.1 Sabbata one Substation

Ethiopia has a lot of substations with the primary purpose of providing electric power to different parts of the country. Sabbata-I substation is one of the substations found in Ethiopia to supply electric power to some parts of the Addis Ababa region and Sabbata areas. Sebbeta-I substation is placed at the geographical coordinates of 08°58'41.0" North and 038°40'51.0" East. This substation is allocated in the south of Addis Ababa at kara kore.

The substation has different protection devices including the current transformer, voltage transformer, circuit breaker, bus bar, earthling transformer, surge arrester, grounding, and control systems, and protection panel that functioning both automatically and manually. It has four incoming lines that supply power, and five outgoing lines which provide electric power to neighboring substations, and fifteen feeders that distribute power to customers. The substation has no reactive power controller that is used to control power flow and impact on the power loss and bus voltage profile of the distribution network.

Sabbata-I substation has been interconnected to the grid and also supplied from different sources, such as Gilgel-Gibe-I, sebbata-II substation by two lines, Gefersa substation and kaliti-I with the high voltage level of 230KV. All incoming lines are tapped to the same double Bus bars in sabbata-I substation to which three autotransformers of capacity 125MVA, 230/132KV are connected. And also, sabbata-I substation is interconnected to the substation nearest to it through the voltage level of 132KV outgoing line such as Addis West with two lines (AW₁ & AW₂), Gefersa substation, kaliti-I substation. The other outgoing line is the line that feeds Gedja substation through three winding transformers of capacity

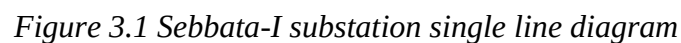
25/25/10MVA,132/45/15KV. The feeders that distribute electric power to different parts of the region are categorized into three parts such as SAB-I-A, SAB-I-B, and SAB-I-C which has 15 outgoing feeders. Feeders 2,6,8,10,11&13 are supplied by SAB-I-A and 1,4,5&7 and 3,9,12,14&15 are supplied by SAB-I-B and SAB-I-C respectively through transformer-1, 2, and 3 with a capacity of 50MVA, 132/15KV. All outgoing feeders from sabbata-I substations are distributed in a radial system. The sabbata-I substation line diagram can be shown in the following figure 3.1 and the system is modeled using Visio13 software

❖ **The Direction of incoming and outgoing feeder**

The sabbata-I substation has three 132kv and one 45kv line which interconnects with the neighboring substation and also has 15kv fifteen (15) outgoing feeders that supplying some parts of Addis Ababa city and the Oromia special zone. The substation power transformer provides power to a variety of consumers, including residential, commercial, and industrial loads. There are no separate feeders for residential, industrial, or commercial use at this substation. The following is a list of the feeders of the substation

- ✓ **Gilgel Gibe-I:** the incoming line from the generation with 230Kv voltage level
- ✓ **Sabbata-II(line 1&2):** supply power to sabbata-I substation by two lines(230kV)
- ✓ **Geffersa line:** incoming line that supplies power to sabb-I substation(230kV)
- ✓ **KAL-I line-** It provides power to the kality-I substation via a 132kV transformer.
- ✓ **ADW-1&2 line:** supplies Addis west substation through 132KV transformer.
- ✓ **GAf line** – it goes to Gefersa substation through a 132KV transformer.
- ✓ **Gedja line-** it supplies Gedja substation through a 45KV transformer.
- ✓ **F1-**supplies to Around Ayer tena, koshe sefer up to Jemo-2 condominium, fana sefer plastic factory, fana sefer inside liul plastic factory
- ✓ **F2-**it goes through underground cable from substation and supply to area Welete, around Noc, Sebata dima,Yes Water Factory, Hora food complex, Meta Brewery Factory, Berchiko Fabrica, Arba minch cherkacherk, Sebata biherawi alchohol up to sabbata.
- ✓ **F3-** supply to Zenebework woreda-5 tena tabia, Kolfe industrial college, Holland Embassy and Torhiloch Hospital up to Keranyo.
- ✓ **F4-** goes with underground cable supply to half of Bethel area and Berchuko Fabrica, gulele condominium.
- ✓ **F5-** its supply to Kenteri, Butajra mazorya, Noc and Waliya Metal Factory,
- ✓ **F6** –gives toJemo 2 condominium water pump, Furii, and Ayka Addis Factory

- Where; L –outgoing lines



3.2.2 Substation Transformer Data

Sabbata-I substation has currently operated with different transformer capacities and voltage levels. The first three transformers are operating to step down the high voltage(230KV) supplied by different power sources such as Gibe-I hydropower, Gefersa substation, and Sabbata-II substation, their capacity is 125MVA, 230KV/132KV. These transformers convert the incoming 230KV into 132KV. The other three transformers which have a capacity of 50MVA,132/15KV convert 132KV into 15KV to supply fifteen outgoing feeders of SAB-I-A, SAB-I-B, and SAB-I-C. And the other three winding transformers with a rating of 25/25/10MVA are functioning to step down 132kv into 45kv, 15kv to feed the Gedja substation. The data for the total number of transformers with their capacity available in Sabbata-I substation is summarized in the following table.

Table 3.1 the transformer data of sabbata-I substation

No	Station name	Voltage ratio(KV)	Equipment	Rating (MVA)	Peak load MW	Remark
1	SEBETA-I	230/132	AT 1	125	91	
2	SEBETA-I	230/132	AT 2	125	—	down b/c protection equipment unavailability
3	SEBETA-I	230/132	AT 3	125	91	
4	SEBETA-I	132/45/15	Transformer-1	25/25/10	21.1/14.2/6.9	
5	SEBETA-I	132/45/15	Transformer-2	12/12/4.0	11.2/11.2/0	15 kV idle
6	SEBETA-I	132/15	Transformer-3	50	41	
7	SEBETA-I	132/15	New traformer	50	45.57	

3.2.3 Capacity of the Outgoing feeders of Sabbata-I Substation

In an electrical distribution system, one of the critical reasons for power loss and poor voltage profile is overloading the distribution line due to the limited capacity of the conductor. The following table shows the total information of Sabbata-I substation outgoing feeders such as type of cable, the capacity of each feeder, relay setting, over current setting value, and CT ratio is summarized in the following table 3.2.

Table 3.2 the general data of outgoing feeder from Sebbata-I substation

Feeder Name	Cable				CT Ratio			Relay Setting		
	C.S.A (mm2)	Type	C.C.C (A)	MW	Ratio	A	MW	setting	A	MW

F1	3 core 120	CU	325	7.6	800/5	800	18.7	0.42XIn	336	7.9
F2	2X240	AL	834	19.5	800/5	800	18.7	0.8*In	640	
F3	1X300	CU	599	14.0	800/1	800	18.7	1Xin	800	18.7
F4	2X240	AL	1064	24.9	800/5	800	18.7	0.82XIn	656	15.3
F	3 core 120	CU	325	7.6	800/5	800	18.7	0.62XIn	496	11.6
F6	2X240	AL	834	19.5	800/5	800	18.7	0.4*In	320	
F7	3 core 240	CU	455	10.6	1200/5	1200	28.1	0.35XIn	420	9.8
F8	2X240	AL	834	19.5	800/5	800	18.7	0.4XIn	320	7.5
F9	1X300	CU	599	14.0	800/1	800	18.7	0.6*In	480	11.2
F10	2X240	AL	834	19.5	800/5	800	18.7	0.6XIn	480	11.2
F11	2X240	AL	834	19.5	800/5	800	18.7	0.6XIn	480	11.2
F12	1X300	CU	599	14.0	800/1	800	18.7	0.8*In	640	14.9
F13	2X240	AL	834	19.5	800/5	800	18.7	0.55XIn	440	10.3
F14	1X300	CU	599	14.0	800/1	800	18.7	0.5*In	400	9.4
F15	1X300	CU	599	14.0	800/1	800	18.7	0.91XIn	728	17.0

3.2.4 Length and Capacity of Each Feeder.

The distance coverage of the distribution feeder can determine the performance of the line. As the length of the feeder become elongated, the capability to deliver power may decrease and can cause system power losses and voltage drop especially at the end of the line. In load flow analysis, the distance coverage of the feeder is very important to evaluate the existing status of the line. The length, maximum capacity of the feeder can withstand the peak load and the total number of transformers in each feeder are the main factor that should be considered during designing, and its shown in table 3.3 below.

Table 3.3 length of the feeder from the substation

Name of the feeder	Distance coverage In (Km)	Number of transformers	Peak load		Name of the feeder	Distance In (Km)	Number of transformers	Peak load	
			Current (A)	Power (MW)				Current (A)	Power (MW)
F1	10.8	57	270	6.3	F9	24.4	74	287	6.7103
F2	40.12	170	506	11.8	F10	1.3	77	296	6.9
F3	25.7	82	440	10.2876	F11	24.2	123	460	10.7
F4	27.3	64	642	15.01	F12	27.83	69	460	10.755
F5	19.8	8	28	0.6	F13	27.4	65	355	8.3
F6	20.1	2	38	0.8	F14	11	12	100	2.338
F7	19.5	70	250	5.8	F15	24.3	24	492	11.503
F8	16.9	8	153	3.5					

3.2.5 Yearly Peak Load and Minimum Load of the Feeders

In the power system distribution network analysis, the value of the monthly peak, average, and minimum load of the feeder must be conducted to determine the reason for power loss and weak voltage profile-related problems. The one cause of line loss and poor voltage profile in a distribution system is due to feeder overloading. The following table 3.4 illustrates the peak and minimum load of the feeders over two years. However, the peak and minimum load of each feeder are from recorded data in each month during 2019 and 2020 which are tabulated in Appendix A in detail.

Table 3.4 peak load and minimum load of the outgoing feeders during 2020

Bay/Line	Peak load				Minimum load			
	Power			Power				
	MW	Current (A)			MW	Current (A)		
		R	S	T		R	S	T
F1	7.6	611	611	611	0.14	6	6	6
F2	12.1	590	590	590	0.02	1	1	1
F3	11.7	492	492	492	0.35	15	15	15
F4	11.2	679	679	679	0.02	2	2	2
F5	1.5	357	357	357	0.01	1	1	1
F6	0.95	40	40	40	0.02	0.5	0.5	0.5
F7	6.4	394	394	394	0.19	8	8	8
F8	4.6	236	236	236	0.07	3	3	3
F9	8.8	368	368	368	0.3	11	11	11
F10	9.4	397	397	397	0.7	28	28	28
F11	11.3	476	476	476	0.83	35	35	35
F12	13.1	552	552	552	0.20	10	10	10
F13	8.4	355	355	355	0.16	7	7	7
F14	2.4	102	102	102	0.00	0	0	0
F15	12.1	510	510	510	0.5	21	21	21

The following figure 3.2 shows the load demand of all outgoing feeders from sabbata-I substation during 2020, and the graph illustrates the peak, minimum and average load of the feeder. As it can be seen that the feeder-12 has more peak load demand than the other feeders that means the feeder is more vulnerable to power interruption due to overloading of the system. From the status of the sabbata-I distribution feeders of minimum, average, and a

peak load of each outgoing line, the highest peak load is taking place on feeder twelve at the voltage level of 15KV, while the minimum load value occurs at feeder six.

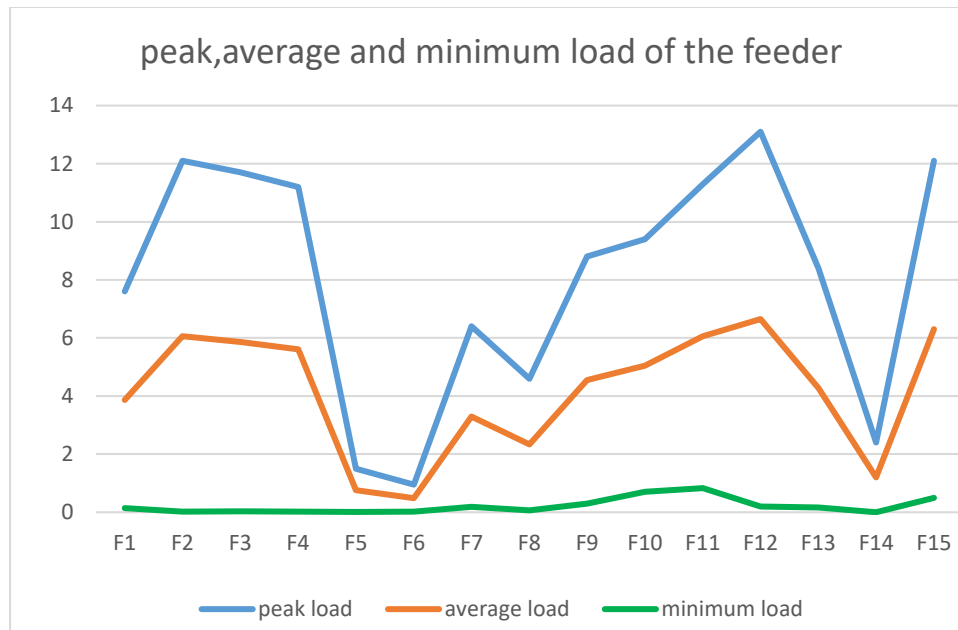


Figure 3.2 peak, average, and minimum load of each feeder

Sabbata-I substation has also a problem of power interruption with long duration due to different reasons and the most cause of power interruption occurs in this station are due to short circuit, earth fault, under frequency, and overload of the line. Line overloading is one of the factors which can disturb the distribution system operation that may cause power loss, varying voltage profiles, and lead the system to voltage instability. As the recorded data indicates, the outgoing feeder of the Sabbata-I substation has highly a problem of overloading for the last two years (2019/2020 due to the increase of power demand. It can be seen from Appendix-B; feeder-12 is more suffered from power interruption with a long duration due to the overloading.

3.2.6 Sabbata-I Distribution Line Arrangements

Overhead distribution conductors should be symmetrically arranged, as shown in Figure 3.3 below, or equidistant from each other so that each phase's flux linkages and inductance are equal. Even if the currents in the conductors are balanced, if the conductor structure is asymmetrical, the inductance would be different, resulting in unequal voltage drops in the three phases. As a result, the voltage at the receiving end will be different for each step. To ensure that voltage drops are equal in all conductors, it is common practice to arrange the conductors symmetrically or to interchange the location of the conductors at regular intervals along the line such that each conductor occupies the original position of any other conductor

over an equal distance. Figure 3.3 depicts the existing overhead conductor system for the Sabbata-I feeder-12, and the resistance and reactance of the line are calculated accordingly.

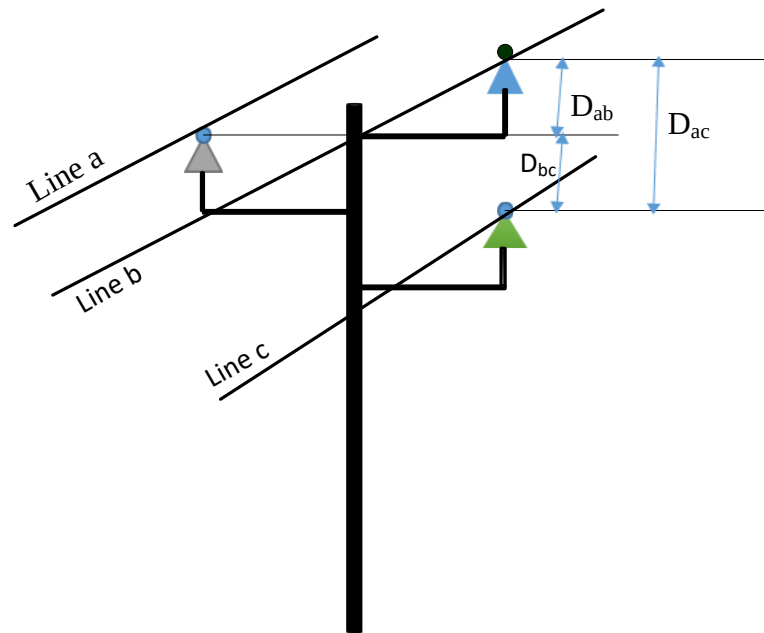


Figure 3.3 Overhead Conductor Arrangement of Sabbata-I Feeder

❖ The impedance of Distribution Line

Overhead lines have resistance and reactance, which restrict current movement. For voltage drop, power flow, short circuit, and line loss calculations, these impedance values are needed. Impedances can be calculated using Carson's equations with no assumptions or impedances can be estimated from tables with a variety of assumptions depending on the degree of accuracy needed. The distribution line conductors used at the Sabbata-I substation are all aluminum conductors (AAC). It has a very low specific mechanical resistance, is utilized for short lengths rather than long spans, and is mostly employed in urban areas to provide perfect cable support, takes up less space, and is simple to install. Table 3.5 shows the features of an AAC-type conductor.

Table 3.5 Standard of conductor

Conductor type	Nominal Area (mm ²)	Real Area (mm ²)	Stranding and wire diameter	Overall Diameter (mm)	Actual Diameter (mm)	GMR	Resistance (Ω/Km)	Reactance (Ω/Km)
AAC	25	24.2	7/2.1	6.3	5.56	1.88	1.181	0.37367
AAC	50	49.5	7/3.00	9	7.9377	2.88	0.5785	0.3470
AAC	95	93.5	19/2.5	12.5	10.8975	4.129	0.3085	0.32441

3.2.7 Single Line Diagram Representation of the Selected Feeder

The thesis work focus on medium 15kv overhead outgoing feeders of Sabbata-I substation which distribute power to the distribution transformer and the feeders are supported with a concrete pole. The substation has 15 feeders which feed the power to residential, commercial, and industrial surrounding the substation, however, to limit further the scope only one feeder of the substation was selected as a case study. The selected feeder is feeder-12 of Sabbata-I substation and it is radially configured. The feeder has more vulnerable to power interruption with long-duration outages and the cause of the interruption is mostly due to the overloading of the feeder which leads the system to power quality problems includes voltage drop, minimum voltage stability margin, and increase system power loss. Among the others feeder, it has high peak demand, and long-distance coverage from substations because of this reason, the feeder is preferred as a base case study network. The feeder has eighty-nine buses, 88 branches, sixty-nine (69) distribution transformers and is constructed from different types of aluminum conductors including AAC-35, AAC-50, and AAC-95 with a total length of 27.83Km. The single diagram of the selected feeder is drawn by visio13 software as shown in figure 3.4 below.

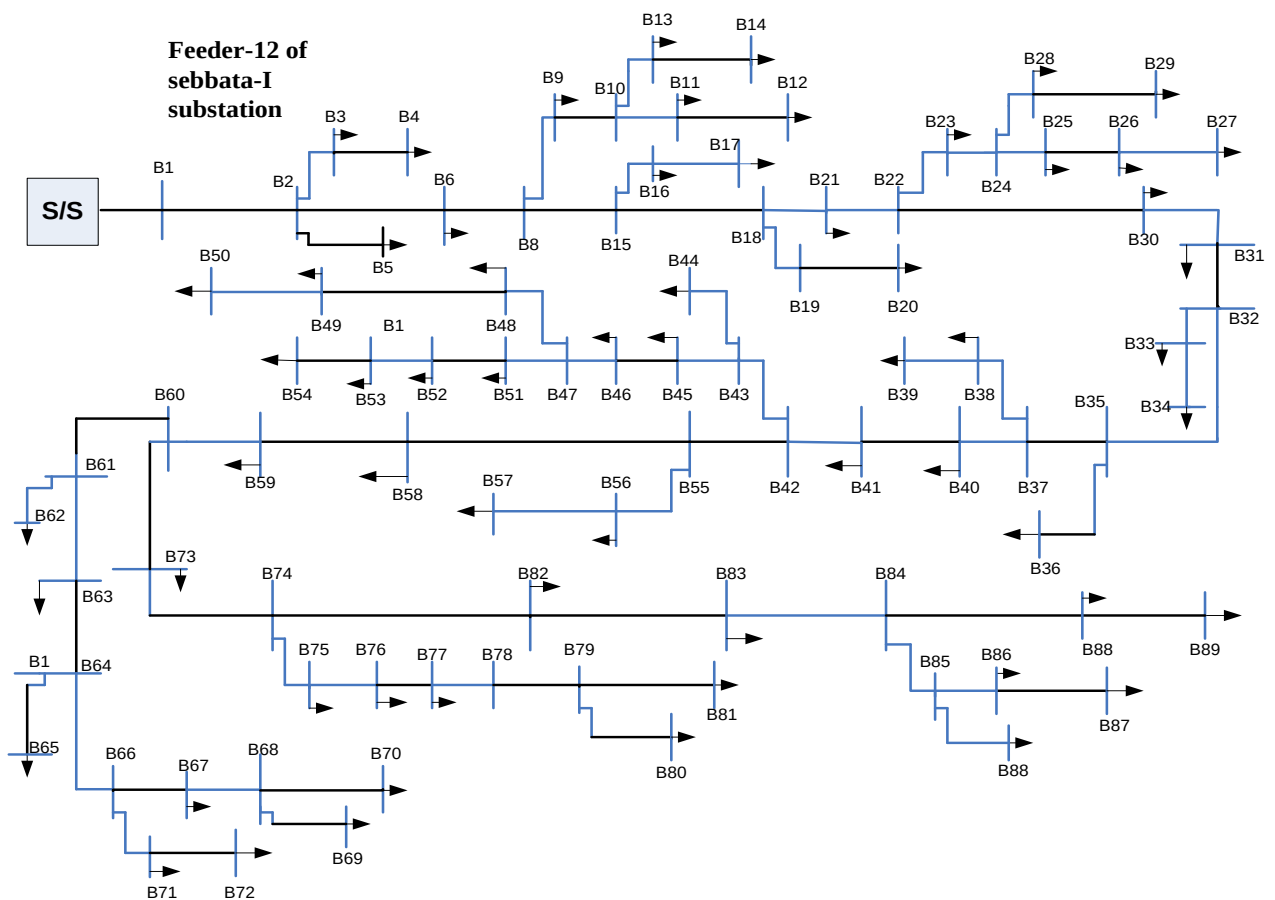


Figure 3.4 Sabbata-I substation feeder-12 single line diagram

3.2.8 Line and Bus Data of the Feeder

Knowing each distribution feeder parameter, such as resistance, reactance, segment distance, active, and reactive power is important when studying distribution line performance. This can be obtained by a different method. The type of conductor that is listed in above table 3.5 and the segment distance of the conductor are used to measure the positive sequence impedance of each branch. The distance of each segment and type of conductor has been collected through the coordination of the installed feeder. Therefore, the following impedance (resistance and reactance) value is calculated manually depending on the distance, and nature of the conductor that is used during the installation of the selected feeder. The size of each distribution transformer is collected from its nameplates with the aid of its GIS coordination by using QGIS software. The Ethiopian electric utility (EEU), distribution line operation, and maintenance room collected the maximum active and reactive power measured with a clamp meter at each load node secondary side of the distribution transformer at different times which is used to do the load flow analysis of the system. All buses, sending end, receiving end, type of conductor, length of each segment line, resistance, reactance, active and reactive power are tabulated in table 3.6 as shown below.

Table 3.6 line and bus data of Sabbata-12 feeder

BUS	Sending End	Receiving end	Type of conductor	Length of conductor (KM)	Resistance (Ω)	Reactance (Ω)	Receiving peak load	
							kW	kVAr
1	1	2	AAC-95	0.13064	0.0404	0.04173	-----	-----
2	2	3	AAC-50	0.3422	0.198	0.11676	147.3	113
3	3	4	AAC-50	0.175	0.1013	0.05971	123.2	102.4
4	2	5	AAC-35	0.05387	0.0498	0.01898	128.1	111.1
5	2	6	AAC-95	0.02182	0.00673	0.00695	-----	-----
6	6	7	AAC-50	0.051	0.02951	0.0174	34.06	25.55
7	6	8	AAC-95	0.5763	0.1778	0.18355	-----	-----
8	8	9	AAC-50	0.2972	0.172	0.1014	87.4	58.52
9	9	10	AAC-50	0.17432	0.101	0.0595	-----	-----
10	10	11	AAC-50	0.244	0.1412	0.0833	183.8	132.9
11	11	12	AAC-50	0.5248	0.30365	0.17906	159	119.3
12	10	13	AAC-35	0.13147	0.122	0.04633	126.8	106.4
13	13	14	AAC-35	0.1917	0.17722	0.06756	213.5	163.4
14	8	15	AAC-95	0.0663	0.02045	0.02112	----	-----
15	15	16	AAC-50	0.3864	0.22357	0.13182	173.4	132.6
16	16	17	AAC-50	0.727	0.421	0.2481	164.3	124.8
17	15	18	AAC-95	0.22687	0.06997	0.07226	-----	-----
18	18	19	AAC-50	0.3861	0.2234	0.1317	97.8	65.82
19	19	20	AAC-50	0.7249	0.42	0.24734	90.08	67.56
20	18	21	AAC-95	0.1801	0.1042	0.06145	397.9	298.4

21	21	22	AAC-50	0.1011	0.0585	0.0345	----	-----
22	22	23	AAC-50	0.0486	0.02812	0.01658	63.8	47.85
23	23	24	AAC-50	0.02768	0.01602	0.00944	-----	-----
24	24	25	AAC-50	0.0974	0.0564	0.03323	113.6	85.2
25	25	26	AAC-50	0.157	0.091	0.05356	128.8	109.1
26	26	27	AAC-50	0.1502	0.08691	0.05124	90.2	65.18
27	24	28	AAC-50	0.07832	0.04532	0.02673	46.76	35.07
28	28	29	AAC-50	0.169	0.0978	0.05767	95.6	69.2
29	22	30	AAC-95	0.0631	0.01946	0.0201	54.13	40.6
30	30	31	AAC-95	0.26678	0.0823	0.085	123.3	92.46
31	31	32	AAC-95	0.0334	0.0103	0.01064	-----	-----
32	32	33	AAC-50	0.2776	0.16062	0.09472	427.2	320.4
33	33	34	AAC-50	0.31	0.1794	0.10577	138.9	109.5
34	32	35	AAC-95	0.0567	0.0175	0.0181	-----	-----
35	35	36	AAC-35	0.11	0.102	0.03876	883.3	664.7
36	35	37	AAC-95	0.3042	0.09382	0.09689	-----	-----
37	37	38	AAC-95	0.2937	0.09058	0.09355	225.8	174.32
38	38	39	AAC-50	0.168	0.09721	0.05733	158.7	111.3
39	37	40	AAC-50	0.22	0.1273	0.07506	102.9	77.16
40	40	41	AAC-50	0.08362	0.0484	0.02853	129	96.72
41	41	42	AAC-50	0.0345	0.02	0.0118	-----	-----
42	42	43	AAC-35	0.190	0.17566	0.067	127.4	90.6
43	43	44	AAC-35	0.14884	0.13761	0.05245	148.5	111.8
44	43	45	AAC-35	0.9279	0.85785	0.327	32.4	19.23
45	45	46	AAC-35	0.2474	0.2287	0.0872	70.92	53.19
46	46	47	AAC-35	0.22434	0.21	0.0791	-----	-----
47	47	48	AAC-50	0.3494	0.2022	0.11922	128.6	92.4
48	48	49	AAC-50	0.149	0.0862	0.0508	149.4	112.3
49	49	50	AAC-50	0.610	0.353	0.208	137.7	110.9
50	47	51	AAC-35	0.7493	0.693	0.264	60.4	45.3
51	51	52	AAC-50	0.09842	0.05695	0.03358	36.92	27.72
52	52	53	AAC-50	0.1074	0.0622	0.0367	31.6	23.7
53	53	54	AAC-50	0.142	0.0822	0.0485	179.7	133.2
54	42	55	AAC-95	0.2138	0.0141	0.0681	-----	-----
55	55	56	AAC-50	0.536	0.310	0.183	59.38	44.53
56	56	57	AAC-50	0.81747	0.473	0.27893	99.6	74.7
57	55	58	AAC-95	0.01765	0.00544	0.00622	107.6	80.7
58	58	59	AAC-95	0.0949	0.0293	0.03022	127.4	102.3
59	59	60	AAC-95	0.08992	0.02773	0.02864	-----	-----
60	60	61	AAC-95	0.11456	0.03533	0.0365	-----	-----
61	61	62	AAC-50	0.41	0.2373	0.1399	99.68	74.76
62	61	63	AAC-50	0.9681	0.561	0.3303	67.2	50.4
63	63	64	AAC-50	0.3302	0.1910	0.11266	164.2	122.7
64	64	65	AAC-50	0.11822	0.0684	0.04033	116	87
65	64	66	AAC-50	1.9658	1.13742	0.671	-----	-----
66	66	71	AAC-50	1.25187	0.72433	0.4272	105.1	78.84
67	71	72	AAC-50	0.5782	0.334	0.19723	-----	-----
68	66	67	AAC-50	0.3835	0.222	0.13085	132.3	99.24
69	67	68	AAC-50	0.7931	0.4589	0.271	-----	-----
70	68	69	AAC-50	0.3342	0.1934	0.114	142.8	105.3

71	68	70	AAC-50	0.454	0.2627	0.155	67.2	50.4
72	60	73	AAC-50	0.2575	0.14899	0.08786	190.45	123.26
73	73	74	AAC-50	0.1256	0.0727	0.04286	-----	-----
74	74	75	AAC-50	0.05628	0.03257	0.01921	163.74	126.23
75	75	76	AAC-50	0.2046	0.1184	0.06981	34.06	25.55
76	76	77	AAC-35	0.1774	0.164	0.06252	114.2	85.68
77	77	78	AAC-35	0.556	0.514	0.196	60.96	45.72
78	78	79	AAC-35	0.0567	0.05242	0.02	-----	-----
79	79	80	AAC-50	0.1943	0.11243	0.0663	154.34	123.25
80	79	81	AAC-50	0.08024	0.04643	0.0274	182.4	136.8
81	74	82	AAC-50	0.2898	0.1677	0.0989	127.6	112.96
82	82	83	AAC-50	0.1567	0.091	0.0535	854.4	640.8
83	83	84	AAC-50	0.1117	0.06463	0.03811	-----	-----
84	84	85	AAC-50	0.9693	0.561	0.33071	-----	-----
85	85	86	AAC-50	0.19734	0.1142	0.06733	79.45	65.86
86	86	87	AAC-95	0.2625	0.081	0.08361	145.1	123.8
87	85	88	AAC-50	0.3393	0.19632	0.11577	155.4	124.6
88	84	89	AAC-50	0.1891	0.1094	0.06452	132.3	99.24

3.3 The Selected Reactive Power Compensator

From the customer point of view, a power quality problem in a distribution system is caused by a high R/X ratio in distribution networks. Voltage drop, a lagging power factor, and instability are all main disadvantages. In a radial distribution network, these issues result in system power losses, a low voltage profile, and network security issues.

Various equipment has been used to enhance the performance and effectiveness of the distribution system to fulfill load demand. The appropriate reactive power injection in the distribution system will solve the power quality problems. With the aid of compensating devices, reactive power can be injected into the radial distribution network. so we need to use highly advanced pieces of equipment for power loss reduction and voltage profile improvement of the distribution network. such types of equipment are Shunt capacitors, regulators, shunt and series reactor, Automatic voltage restorer(AVR), and recently created Distribution Network Flexible AC Transmission (D-FACTS) such as Distribution static compensator (DSTATCOM), Unified Power Flow Conditioner (UPQC), interline power flow controller(IPFC), and Static Synchronous Series Compensator(SSSC) are the most common compensating devices used in the distribution system[46].

Amongst these, the DSTATCOM is one of the most effective devices. Therefore, DSTATCOM has few benefits over the other compensating devices, including low power losses, a smaller amount of harmonic production, automatic operation, high regulatory capability, continuous operation, compact size, and low cost. Furthermore, it will not trigger

any operational issues such as resonance or harmonics distortion[46]. This device plays an important role in improving voltage regulation, voltage balancing, improving poor power factors, minimize harmonics, and reducing power losses, etc. of the distribution system under both steady-state and dynamic conditions [47]. Due to the overflowing of power system load, DSTATCOM is expected to play a significant role in radial distribution systems. The optimal placement of DSTATCOM maximizes the load ability, power loss reduction, stability enhancement, reactive power compensation, and power quality enhancement whereas inappropriate allocation in some situations can reduce the benefits, will lead to collapse, and even endanger the entire system operation[48][46].

3.3.1 Distribution Static Compensator

Distribution Static Compensator(DSTATCOM), is a type of shunt DFACTS device that controls power flow and improves transient stability on electrical power networks by using force-commutated power electronics (i.e. GTO, IGBT). DSTATCOM supplies or injects the needed amount of current at the point of connection to increase the voltage profile at the load bus where DSTATCOM is attached and regulates it to desirable reference values in the event of heavy loading conditions or short circuits. DSTATCOM's ability to inject reactive power over a long period is virtually impossible due to the energy storage capacity. As a result, the process is mostly in steady-state, with DSTATCOM and the device exchanging reactive power. DSTATCOM can control and corrects the bus voltage and power factor because it acts as the synchronous voltage source. DSTATCOM reduces voltage fluctuations by comparing the line waveform to the reference signal regularly and injecting or absorbing the needed amount of reactive current based on the error. The magnitude of source used in DSTATCOM will decide the direction and magnitude of the reactive current. A schematic diagram of D-STATCOM integrated into a bus k is shown in Figure 3.5 [39].

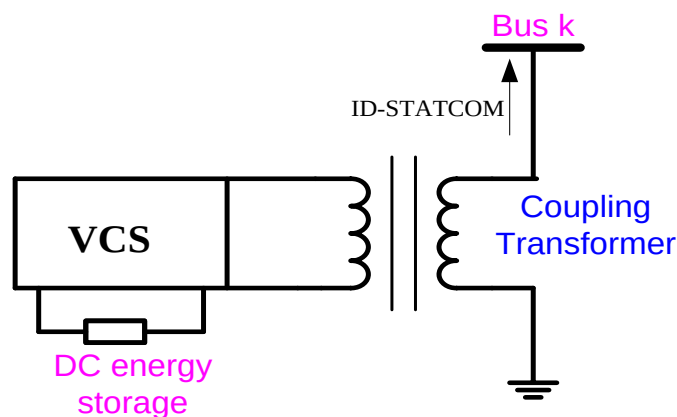


Figure 3.5 DSTATCOM connected to a certain bus k [49]

3.3.2 Components of D-STATCOM

A three-phase inverter (generally a PWM inverter) using SCRs, MOSFETs, or IGBTs, a D.C capacitor that provides the inverter with D.C voltage, a link reactor that connects the inverter output to the AC supply side, and filter components to filter out the high-frequency components caused by the PWM inverter makeup D-STATCOM. The inverter generates a three-phase voltage from the DC Side capacitor. The main role of the capacitor bank is supplying the constant DC voltage, which is converted to a three-phase voltage. The AC output voltage feeds a coupling transformer that is common coupling with the radial distribution system. The AC supply is synchronized with this. The connection inductor connects the device voltage to the AC power supply [49].

3.3.3 Basic Operating Principle of D-STATCOM

D-STATCOM is similar to a synchronous machine in that it provides a lagging current when under excited and a leading current when overexcited. The D-STATCOM voltage is injected in phase with the line voltage, and there is no power exchange with the network in this case; instead, only reactive power is injected (or absorbed) by the DSTATCOM. The reactive power exchange with the network is accomplished by varying the output voltage amplitude. At the connection point, if the voltage magnitude(V_s) is higher than the magnitude of the voltage source(V_{sc}), DSTATCOM work as an inductor and absorbs the excess reactive power similarly, if the voltage magnitude(V_s) is lower than the magnitude of a voltage source(V_{sc}), DSTATCOM work as a variable capacitor and injects the required reactive power. D-STATCOM does not generate or absorb reactive power if V_{sc} equals V_s , and the reactive power is zero (No-load mode)[50]. DSTATCOMS has three operating modes, as shown in Figure 3.6:

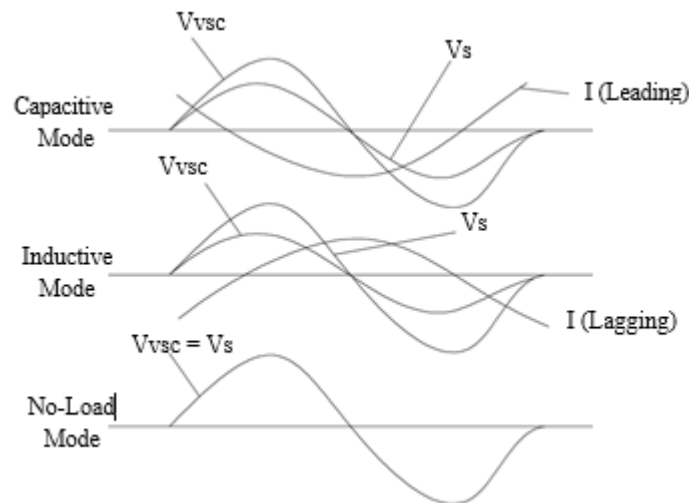


Figure 3.6 Operating Modes of D-STATCOM[50]

3.3.4 Applications of D-STATCOM

D-STATCOMs are used to maintain voltage stability in long-distance transmission networks, power substations, distribution systems, and heavy industries. Static synchronous compensators are also mounted at different points in the power system to perform the following basic functions. D-STATCOM performs the following basic functions as voltage regulation and reactive power compensation, harmonic current compensation, power factor correction, voltage flicker suppression, Uninterrupted power supply when used as a power storage device[47].

3.3.5 Mathematical Modeling of D-STATCOM

The D-STATCOM is illustrated in Figure 3.8, and its static model was used to analyze the distribution system load movement. Since the system supports reactive power at the attached bus, the voltage profile of the bus where the device is connected will increase, as will the voltage at the buses due to the reactive power support and loss reduction. As a result, the D-STATCOM will more affect the voltages of nearby buses. At the candidate bus, the current voltages are $V_{(m+1)}$, and at the previous bus, they are V_m . The current $I_{(m+1)}$ is the product of adding I_M and I_{DS} . The current injected by DSTATCOM is called I_{DS} , and it is in quadrature with the voltage. As a result, after installing D-STATCOM, the expression for new voltage is written as follows[51]. Figure 3.7 shows a basic two-bus radial distribution system[52].

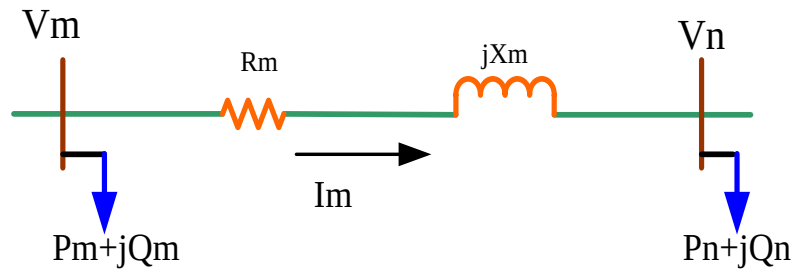


Figure 3.7 Two bus radial distribution system

For the two-bus system, the voltage equation is as follows

$$V_{m+1} = V_m \angle \theta_m - (R_m - jX_m) I_m \angle \delta \quad (3.1)$$

By installing D-STATCOM, the voltage values at the bus where it is installed and at the neighboring bus change. The new voltages are V'_{m+1} at the candidate bus and V'_m at previous neighboring buses changes. The current changes to I'_m which is the summation of I_M and I_{DS} . Where I_{DS} is the current injected by D-STATCOM and is in quadrature with voltage.

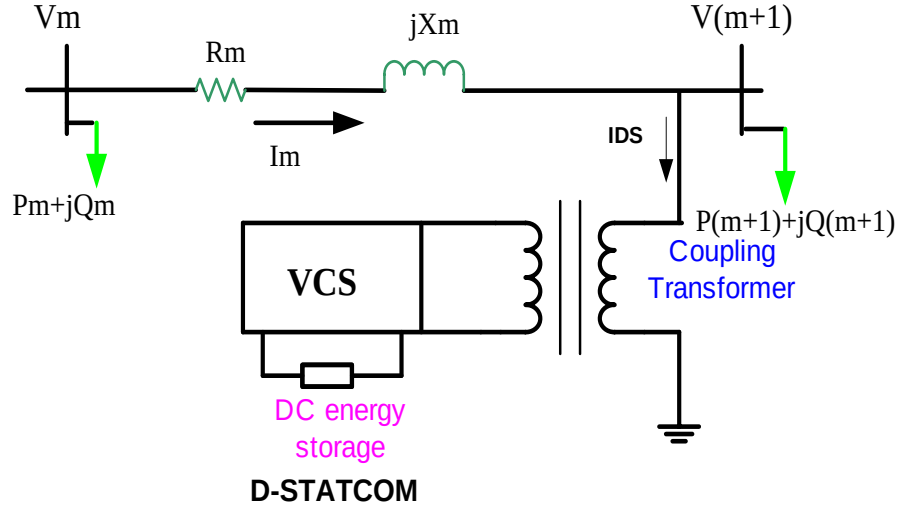


Figure 3.8 Two bus radial distribution system with D-STATCOM [53]

In a conventional radial system, voltages at the buses are often less than 1 p.u. Assuming that the voltage on bus 'm+ 1' is less than 1 p.u, DSTATCOM is installed on this bus to improve the voltage profile. For steady-state modeling of D-STATCOM, it is installed at the bus as shown in Figure 3.8. As a result, the new voltage after installing D-STATCOM is expressed as [49]:

$$V_{m+1} = V_m \angle \theta_m - (R_m - jX_m)I_m \angle \delta + I_{DS} \angle \left(\frac{\pi}{2} + \theta_{m+1} \right) \quad (3.2)$$

Here θ'_{m+1} , θ'_m and δ is the phase angle of V'_{m+1} , V'_m and I_m respectively. When the real and imaginary parts of the above equations are separated, we get

$$V'_{m+1} \cos \theta'_{m+1} = \text{Real}(V'_m \angle \theta'_m) - \text{Real}(Z_m I_m \angle \delta) - R_m I_{DS} \cos \left(\frac{\pi}{2} + \theta'_{m+1} \right) + X_m I_{DS} \sin \left(\frac{\pi}{2} + \theta'_{m+1} \right) \quad (3.3)$$

$$V'_{m+1} \sin \theta'_{m+1} = \text{Imag}(V'_m \angle \theta'_m) - \text{Imag}(Z_m I_m \angle \delta) - X_m I_{DS} \cos \left(\frac{\pi}{2} + \theta'_{m+1} \right) + R_m I_{DS} \sin \left(\frac{\pi}{2} + \theta'_{m+1} \right) \quad (3.4)$$

Now by making some assumptions

$$V'_{m+1} = b; h_1 = \text{Real}(V'_m \angle \theta'_m) - \text{Real}(Z_m I_m \angle \delta); h_2 = \text{Imag}(V'_m \angle \theta'_m) - \text{Imag}(Z_m I_m \angle \delta)$$

$$h_3 = -X_m; h_4 = -R_m; I_{DS} = x_1; \theta'_{m+1} = x_2$$

So, equations (3.3) and (3.4) changes to

$$b \cos x_2 = h_1 - h_4 x_1 \sin x_2 - h_3 x_1 \cos x_2 \quad (3.5)$$

$$b \sin x_2 = h_2 - h_3 x_1 \sin x_2 - h_4 x_1 \cos x_2 \quad (3.6)$$

So, from equation (3.5)

$$x_1 = \frac{b \cos x_2 - h_1}{-h_4 \sin x_2 - h_3 \cos x_2} \quad (3.7)$$

And from equation (3.6)

$$x_1 = \frac{bsinx_2 - h_2}{-h_3sinx_2 - h_4cosx_2} \quad (3.8)$$

From equations (3.7) and (3.8), we get

$$\frac{bcosx_2 - h_1}{-h_4sinx_2 - h_4cosx_2} = \frac{bsinx_2 - h_2}{-h_3sinx_2 - h_4cosx_2}$$

By rewriting both side equations, it can be written as

$$bh_4 + (h_1h_3 - h_2h_4)sinx_2 + (-h_1h_4 - h_2h_3)cosx_2 = 0 \quad (3.9)$$

Let $sinx_2 = t$; $(h_1h_3 - h_2h_4) = k_1$; $(h_1h_4 + h_2h_3) = k_2$

So, equation (3.9) changes to

$$bh_4 + k_1t - k_2\sqrt{(1 - t^2)} = 0 \text{ and } bh_4 + k_1t = k_2\sqrt{(1 - t^2)} \quad (3.10)$$

By squaring both sides of the equation, the equation become

$$(k_1^2 + k_2^2)t^2 + 2bh_4k_1t + b^2h_4^2 - k_2^2 = 0 \quad (3.11)$$

This gives

$$t = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \quad (3.12)$$

Where $A = K_1^2 + K_2^2$; $B = 2bh_4K_1$; $C = b^2h_4^2 - K_2^2$

By substituting values of K_1 and K_2 , the equation will be

$$A = (h_1h_3 - h_2h_4)^2 + (h_1h_4 + h_2h_3)^2 \quad (3.13)$$

$$B = 2(h_1h_3 - h_2h_4) + (V'_n) \quad (3.14)$$

$$C = (V'_n \cdot R_m)^2 - (h_1h_4 + h_2h_3)^2 \quad (3.15)$$

Now there are two roots of t . for determining the correct value of root, the boundary considerations are examined

$V'_{m+1} = V_{m+1}$, $I_{DS} = 0$ and $\theta'_{m+1} = \theta_{m+1}$

The result shows that $t = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$ is the correct root of an equation.

Therefore, the bus voltage phase is

$$\theta'_{m+1} = \sin^{-1}\left(\frac{-B \pm \sqrt{D}}{2A}\right) \quad (3.16)$$

D-STATCOM current angle and magnitude is:

$$\angle I_{ds} = \frac{\pi}{2} + x_2 = \frac{\pi}{2} + \sin^{-1} t \quad (3.17)$$

$$|I_{ds}| = x_1 = \frac{V'_{m+1}\cos\theta_{m+1} - h_1}{-h_4\sin\theta'_{m+1} - h_3\cos\theta'_{m+1}} \quad (3.18)$$

Finally, the reactive power injected is

$$jQ_{DS} = (V'_{m+1} \angle \theta_{m+1}) * (I_{DS} \angle (\frac{\pi}{2} + \theta'_{m+1})) \quad (3.19)$$

Where Q_{DS} denotes the complex conjugate[48][51][54].

3.4 Radial Distribution System Power Flow Analysis

Power flow analysis is critical in the planning, control, and operation of power systems to ensure that they are run efficiently. It is important for all network measurements because it concerns the network's efficiency in steady-state operating conditions. A power flow study focuses on many aspects of AC power characteristics such as voltage, voltage angle, real power, and reactive power, and commonly employs simplified notation such as a one-line diagram and per unit system. Power flow studies are critical for both planning future power system expansion and evaluating the best performance of existing systems.

The following parameters are determined by applying load flow analysis of radial distribution network include voltage magnitude and its angle at each node, the current flowing in each branch, loss of power in each branch, input power to the feeder, total power loss in the feeder. The radial distribution network has the characteristics includes network parameters are poor and unpredictable, the R/X ratio is high, nodes and branches are numerous, and load connected changes dynamically[7].

Since load-flow is a non-linear problem, it must be solved iteratively, which requires the use of one or more of the following methods including Backward/forward sweeping, Gauss-Siedel, Newton-Raphson, and Fast decoupled methods. Excluding the Backward/Forward sweep, the others methods are traditional power flow studies and they are not appropriate for load flow studies in radial distribution systems because of the above factor. The backward/forwards sweeping is one of the efficient methods which is used in this work because the convergence potential of these algorithms is evaluated under various loading conditions and R/X ratios, simple, fast, as well as the effect of static load on the algorithms' convergence characteristics and produce precise result over the whole process[7]

3.4.1 Backward/forwards Sweeping for Radial Distribution Load Flow Analysis

The important work to be done before the determination of the optimal placement and size of the distributed static compensator in the distribution system is the power flow solution of the existing system. A power flow method is a significant tool for analyzing the performance of electrical power system networks, and most distribution networks are radial, with a high R/X value, which causes problems with the convergence of traditional load flow algorithms, making it ill-conditioned. It is possible to regard the study distribution network for steady-

state modeling of D-STATCOM, it is installed at the bus as shown in Figure 3.8. as the primary distribution feeder of a three-phase system that is running at a balanced load[1].

For the reason of its simplicity, speed, and robust convergence, as well as low memory requirements for processing with efficiencies and solution accuracies computational, the BFS algorithm is one of the most widely used methods for load flow distribution systems. The BFS algorithm consists of three simple iterative steps based on Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL). The nodal current calculation, backward sweep, and forward sweep are the three stages, which are repeated until convergence is achieved. Two calculations are performed at each step in this method. Load flow analysis can be done by a set of two iterative equations. The first backward sweep is carried out, with voltage calculations beginning at the final node and progressing to the first node. After that, a forward sweep is done, with voltage calculations beginning at the first node and progressing to the last node. Iterations will stop when the mismatch between voltage is very less [7][8]. For the reason, that of its computational efficiencies and system accuracies, the backward/forward sweep load flow method is used as the distribution load flow in this thesis, as is the algorithm described below.

❖ **Algorithm for Forward-Backward Sweep Load Flow**

Voltage drop computation with power flow updates is called forward sweep. Forward sweep starts from the first node and goes towards the end node and at each node KVL and KCL is applied to calculate the voltage on the succeeding node. Its objective is to calculate the voltage at each node starts from the root node. In this power in each branch is kept at the original value to that obtained in backward propagation. Substation voltage is set at 1 p.u in the beginning. The equivalent current injections (ECI), bus injection to the branch-current matrix (BIBC), and branch-current to the bus-voltage matrix (BCBV) are all used in this approach. The complex load S_i for bus- i is written as,

$$S_i = P_i + jQ_i \quad (3.1)$$

Where; $i = 1, 2, 3 \dots N$

❖ **Equivalent Current Injection**

From the specified complex power S_i at bus- i which is expressed in equation (3.1).

From equation 3.1, the equivalent current injection is expressed as:

$$I_i = I_i^r(V_i) + jI_i^i(V_i^k) = \left(\frac{P_i + jQ_i}{V_i^k} \right)^* \quad (3.2)$$

The equivalent current injection at the k th iteration at the i th node in the load flow solution is represented as;

$$I_i^k = I_i^r(V_i^k) + jI_i^i(V_i^k) = \left(\frac{P_i + jQ_i}{V_i^k} \right)^* \quad (3.3)$$

Where S_i is the complex power at the i th bus, P_i is the real power at the i th bus, Q_i is the reactive power at the i th bus, V_k is the bus voltage at the k th iteration for i th bus, I_k is equivalent current injection at the k th iteration for i th bus, I_r is the real part of the equivalent current injection at the k th iteration for i th bus, I_i is the imaginary part of the equivalent current injection at the k th iteration for i th bus.

❖ Formation of BIBC Matrix/Backward Sweep

Forward sweep is the computation of voltage drop with power flow updates. Backward sweep starts from the last node and goes towards starting node and at each node KVL and KCL is applied to calculate the voltage on the proceeding node. using this method power flowing in each branch is calculated assuming voltage at node obtained in the forward sweep. This means that the voltage obtained during the forward sweep is maintained, while the power flowing through each branch is modified during the backward sweep. This implies that the backward sweep starts from the last node and proceeds to the wards start node. The branch currents are obtained as a function of injected currents at each bus by applying Kirchhoff's current law (KCL) to the radial distribution network as shown above in Figure (3.9). The injected currents at each bus are calculated using equation (3.2) and the branch currents B_5 , B_4 , B_3 , B_2 , and B_1 can be formulated as a function of the equivalent current injections and expressed as shown below.

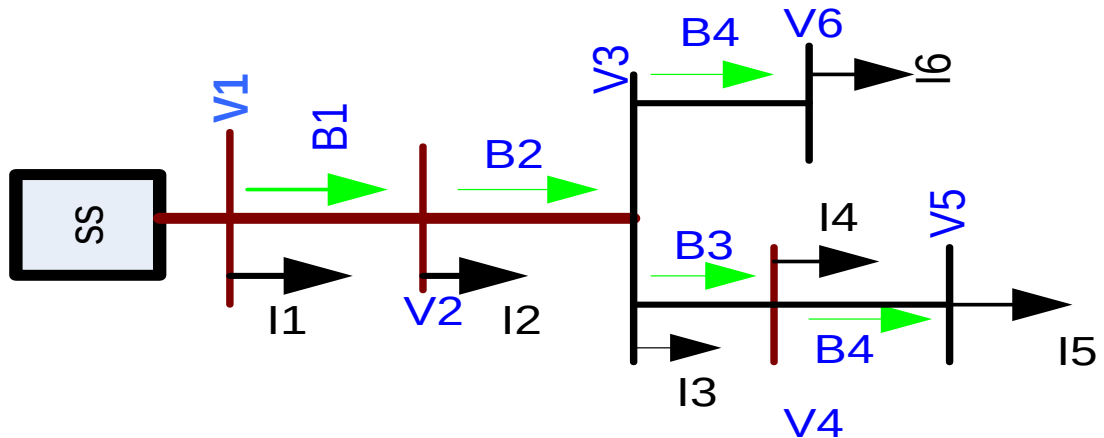


Figure 3.9 Simple radial Distribution Network

$$B_5 = I_6 \quad (3.3)$$

$$B_4 = I_5 \quad (3.4)$$

$$B_3 = I_4 + I_5 \quad (3.5)$$

$$B_2 = I_3 + I_4 + I_5 + I_6 \quad (3.6)$$

$$B_1 = I_2 + I_3 + I_4 + I_5 + I_6 \quad (3.7)$$

Thus, the bus current injections and branch currents (BIBC) matrix can be expressed from the above equations (3.3-3.7) as,

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (3.8)$$

The general form of Eq. (3.8) can be expressed as:

$$[B] = [BIBC][I] \quad (3.9)$$

Where; BIBC is the bus injection branch current for the given sample network is given By

$$[BIBC] = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.10)$$

❖ Formation of BCBV matrix/Forward Sweep

The Branch-Current to Node voltage (BCBV) matrix is the relation of branch currents and bus voltages of a radial distribution network that can be obtained by applying Kirchhoff's Voltage Law (KVL). As shown in Figure 3.9, the voltages of Node 2, 3, and 4 for the relationship between branch currents and bus voltages are expressed as:

$$V_2 = V_1 - (Z_{12}B_1) \quad (3.11)$$

$$V_3 = V_2 - (Z_{23}B_2) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) \quad (3.12)$$

$$V_4 = V_3 - (Z_{34}B_3) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) - (Z_{34}B_3) \quad (3.13)$$

$$V_5 = V_4 - (Z_{45}B_4) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) - (Z_{34}B_3) - (Z_{45}B_4) \quad (3.14)$$

$$V_6 = V_5 - (Z_{56}B_5) = V_1 - (Z_{12}B_1) - (Z_{23}B_2) - (Z_{34}B_3) - (Z_{45}B_4) - (Z_{56}B_5) \quad (3.15)$$

The voltage at the bus i is V_i , while the line impedance between buses i and j is Z_{ij} . From equations (3.11-3.15), the node voltage of the network can be expressed as a function of the branch currents, line parameters, and main substation voltage.

$$\begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{56} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (3.16)$$

$$[BCBV] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & 0 & 0 \\ 0 & 0 & 0 & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \quad (3.17)$$

$$[BCBV] = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & 0 & 0 \\ 0 & 0 & 0 & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \quad (3.18)$$

$$[BCBV] = [BIBC]^T [Z_D] \quad (3.19)$$

Equation (3.19) can be expressed as

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{56} \end{bmatrix} \quad (3.20)$$

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ 0 & Z_{23} & 0 & 0 & 0 \\ 0 & 0 & Z_{34} & 0 & 0 \\ 0 & 0 & 0 & Z_{45} & 0 \\ 0 & 0 & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix} \quad (3.21)$$

$$\Delta V = [BCBV][B] \quad (3.22)$$

$$\Delta V = [BCBV][ZD][B] \quad (3.23)$$

$$\Delta V = [BIBC]^T [ZD][B] \quad (3.24)$$

The general form for the bus voltage at (k+1)th iteration from equation (3.16) can be expressed as:

$$[V_{k+1}] = [V_1] - [BCBV][B] \quad (3.25)$$

The relationships between node current injections and node voltages could be expressed using equations (3.9) and (3.22).

$$[\Delta V] = [BCBV][BIBC][I] \quad (3.26)$$

$$\Delta V = [BIBC]^T [ZD][B][I] \quad (3.27)$$

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

$$[DLF] = [BCBV][BIBC] = [BIBC]^T [Z_D][BIBC] \quad (3.28)$$

Substituting equation (3.27) into equation (3.28), we have

$$[\Delta V] = [DLF][I] \quad (3.29)$$

The stepwise solution for the load flow in the distribution system is as follows:

$$[\Delta V_{k+1}] = [DLF][I_k] \quad (3.30)$$

$$[\Delta V_{k+1}] = [V_1] + [\Delta V_{k+1}] \quad (3.31)$$

❖ Algorithm for Distribution Network Load Flow

The backward forward load flow algorithm described above may have the following steps for load flow solution of distribution networks as shown below:

Step 1: Read the bus, and line data of the selected feeder.

Step 2: Calculate each node's current injection matrix.

Step 3: Calculate the BIBC matrix and determine the branch current.

Step 4: Form the BCBV matrix using steps given in section

Step 5: Calculate the DLF matrix.

Step 6: Set Iteration $k = 0$.

Step 7: Iteration $k = k + 1$

Step 8: Update voltages.

Step 9: If $\max (|V^{k+1}| - |V^k|) > \text{tolerance}$, go to step 5.

Step 10: Compute each branch current and power losses from final node voltages.

Step 11: Display the magnitudes and angles of node voltages, branch currents, and losses.

Step 12: Stop/end

3.5 Particle Swarm Optimization

Particle swarm optimization is a meta-heuristic population-based stochastic optimization approach proposed by Doctor Kennedy and E Eberhart in 1995 that can easily optimize non-linear optimization problems. It is inspired by the social behavior of certain groups of animals. The PSO method employs a group of people to search for promising areas of the search space. The person or each bird or fish is referred to as a particle or agent in this sense, and the flock is referred to as a "Particle Population or Swarm"[55].

The fitness or objective value of each particle is determined by the objective function. This algorithm is based on a very simple concept similar to bird flocking and fish schooling, which is an iterative search technique in which particles travel across a large area of search

space based on the objective function. Each particle explores the entire space by moving in random directions and remembering its previous best solutions from its own experience, as well as the locations of its neighbor particles or the experiences of other particles. A swarm's particles dynamically change their location and velocity by communicating the best positions of all the particles to one another. Finally, as seen in Figure 3.10, all particles in the swarm try to travel into better positions before the swarm finds an optimum solution. The PSO optimization theory is based on the idea of simulating the movement of a group of individuals to find the best solution to a mathematical problem, similar to how birds or fish search for food in a large region, either dispersed or together[56].

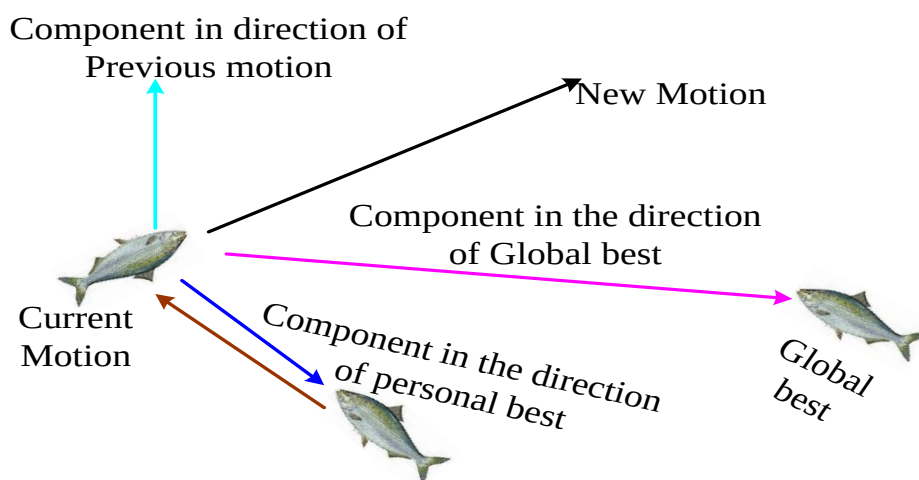


Figure 3.10 Concept of a searching point by PSO[57]

Particle Velocity is defined which directs each particle's position and gets updated in each iteration. Particles gradually move near the optimal due to the best position they have ever experienced and the outstanding solution, which the group has accomplished. The velocity of a particle is modified based on three factors: the particle's previous velocity, its best position thus far, and the best position thus far of the whole swarm.

Therefore; the PSO technique is becoming more common due to its ability to obtain quick convergence, simple implementation, and PSO uses only basic mathematics rather than require any derivative or gradient knowledge[57].

The following are the key benefits of PSO over traditional optimization methods:

In comparison to other optimization techniques, like the Genetic Algorithm, PSO has a faster convergence rate; the search can be carried out by the particle's speed since there is no overlapping and mutation calculation like GA. Optimist particles can transmit information

onto another particle during the development of many generations, and they have a very fast searching speed.

PSO is less reliant on a collection of initial values than other optimization techniques. This algorithm, in comparison to other optimization methods, has a lower effect of parameters on the optimum solution since it has a smaller number of parameters. The PSO method is a gradient-free method. PSO is a very simple algorithm that appears to work well for optimizing a variety of functions[57]. A potential solution of two vectors associated with particle position (X) and velocity (V) vectors is particle coordination. During a search, the particles communicate in a specific way to improve their search experience. The particle with the best solution shares its location coordinates (Pgb) knowledge with the rest of the swarm at the end of each iteration. As a result, the PSO algorithm variable is defined as follows[56]:

The location of the *i*th particle at time *t* is represented by the ‘D’ dimensional vector;

$$X_{id}(t) = (X_{i1}, X_{i2}, \dots, X_{id}) \in S \quad (3.1)$$

The velocity of the *i*th particle at time *t* is a ‘D’ dimensional vector denoted by;

$$V_{id}(t) = (V_{i1}, V_{i2}, \dots, V_{id}) \in S \quad (3.2)$$

The best previous position of each particle at time ‘*t*’ is a point in ‘*S*’, which is denoted by;

$$P_{id} = (P_{i1}, P_{i2}, \dots, P_{id}) \in S \quad (3.3)$$

The global best position attained among entire particles is a point in ‘*S*’, and denoted by;

$$P_{gbd} = (P_{gb1}, P_{gb2}, \dots, P_{gbd}) \in S \quad (3.4)$$

Then, each particle updates its coordinate based on its own best search experience ‘*P_{id}*’ and ‘*P_{gd}*’ according to the following velocity and position update equations. The modification process can be stated mathematically as follows:

$$V_{id}^{t+1} = W * V_{id}^t + C_1 * r_1 * (P_{id}^t - X_{id}^t) + C_2 * r_2 * (P_{gbd}^t - X_{id}^t) \quad (3.5)$$

$$X_{id}^{t+1} = X_{id}^t + V_{id}^{t+1} \quad (3.6)$$

Where: *W*- Inertia weight; *i*=1, 2... *n* and *d*=1, 2... *m*; *c₁*, *c₂*- Acceleration coefficient *r₁*, *r₂*- Two separately generated uniformly spread random numbers in the range [0, 1] added in the model to introduce stochastic nature.

V_{id}^t- Current velocity of the particle ‘*i*’; *V_{id}^{t+1}*- The modified velocity of the particle ‘*i*’

P_{id} - The particle best position value; *P_{gd}* - The groups of the best position value

X_{id}^t - Current search point of a particle; X_{id}^{t+1} - The modified velocity of the searching point of a particle; n - Number of particles in the swarms; m - A particle's number of members (searching space of particle). The following is the inertia weight function

$$W_k = W_{max} - \frac{W_{max} - W_{min}}{t_{max}} \times t \quad (3.7)$$

Where: W_{min} and W_{max} are the minima and maximum inertia weights respectively.

t and t_{max} are the current and maximum iteration. Each particle is represented in the diagram as shown in Figure 3.13[58][59].

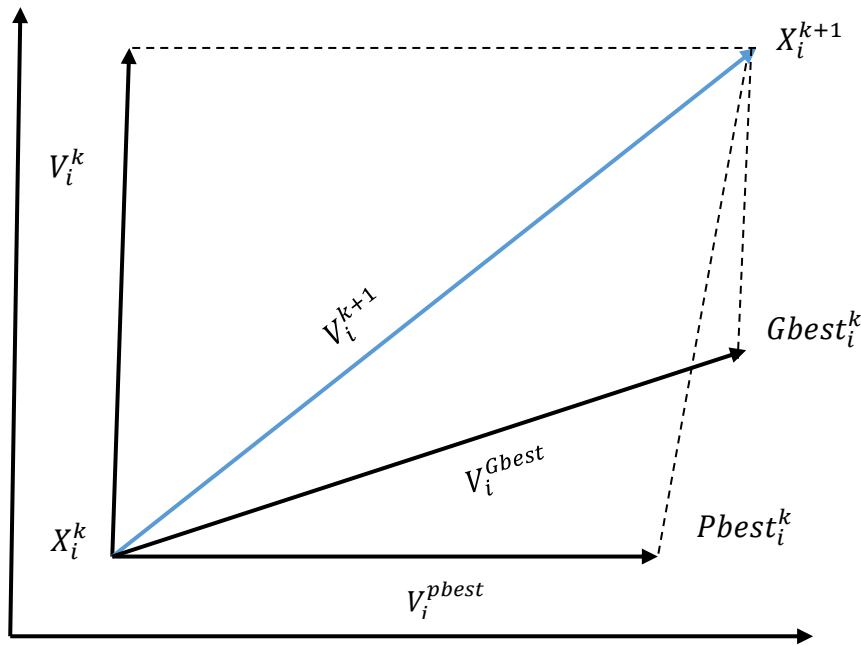


Figure 3.11 PSO search mechanism in multidimensional search space representation[59]

3.5.1 PSO Parameters

The basic important parameters of the PSO algorithm are briefly stated and defined as follows[57].

a) Particle Velocity

One of the derived methods in the PSO algorithm is particle velocity. Its worth is restricted to the bounds. The fitness is determined by the parameters V_{max} and V_{min} , which indicate which regions should be searched between the current and target positions. This is since the particles travel in larger stages, and the solution found might not be ideal. Similarly, particles take longer to enter desired solutions if are too few. In many PSO interactions, is usually set at 12–25% of the variable's dynamic range on each axis.

b) Random Numbers: Random values are in the range [0, 1], which helps to achieve the stochastic behavior of the PSO.

c) Weighting Coefficients

Coefficients of Weighting The weighting of the stochastic acceleration terms is represented by these parameters. The unexpected movement toward, or past, target regions is a function of high-value outcomes. Low values, on the other hand, allow particles to move a long distance before being dragged down. As the number of iterations grows, the parameters can be set in the range (1-2). It is frequently a constant that regulates the rate of relative influence for applications of their typical values $C1=C2= 2$

d) Inertia Weight

A good choice of inertia weight (W) will provide a good mix of global and local searches. The initial inertia weight is normally set to a high value and then gradually reduced during optimization. The inertia weight (W) is adjusted in general according to equation (3.7), 0.2 and 0.9 are acceptable values, respectively.

e) Termination criterion

Following the initial process, the assessment steps are subjected to multiple iterations and objective function tolerances before a stopping criterion is met. The stopping condition is usually the completion of a predetermined maximum number of iterations or the attainment of a certain level of accuracy in the solution.

3.5.2 PSO Implementation Procedures

The population of the PSO algorithm has n -particles, each of which represents a candidate result. Each particle is a D -dimensional real-valued vector, where the number of optimized parameters is ' D '. As a result, each optimized parameter represents a problem space dimension.

❖ Particle Swarm Optimization

The steps of the PSO technique can be described as below:

Step 1: Initialization

Initialize the iteration counter to 1, which generates an initial dimension of n -particles at random. The starting velocity of each particle is generated at random to calculate the goal functions $t_{\max}$, $W_{\min}$, $W_{\max}$, c_1 , and c_2 . The lower and upper bounds of regional limitations are also set in this step.

Step 2: Set iteration count (for PSO) $\text{iter}=1$.

Step 3: While, $\text{maxiter}>\text{iter}$ or tolerance;

Step 4: Objective function calculation

Step 5: Upgrading of both local minimum and the global minimum of particles

Step 6: Particle position update and velocity modification and Modify the velocity of each particle using the equation (3.8);

$$V_{id}^{t+1} = C_1 * r_1 * (P_{id}^t - X_{id}^t) + C_2 * r_1 * (P_{gd}^t - X_{id}^t) \quad (3.8)$$

Then generate the new particles search space based on equation (3.9):

$$X_{id}^{t+1} = X_{id}^t + V_{id}^{t+1} \quad (3.9)$$

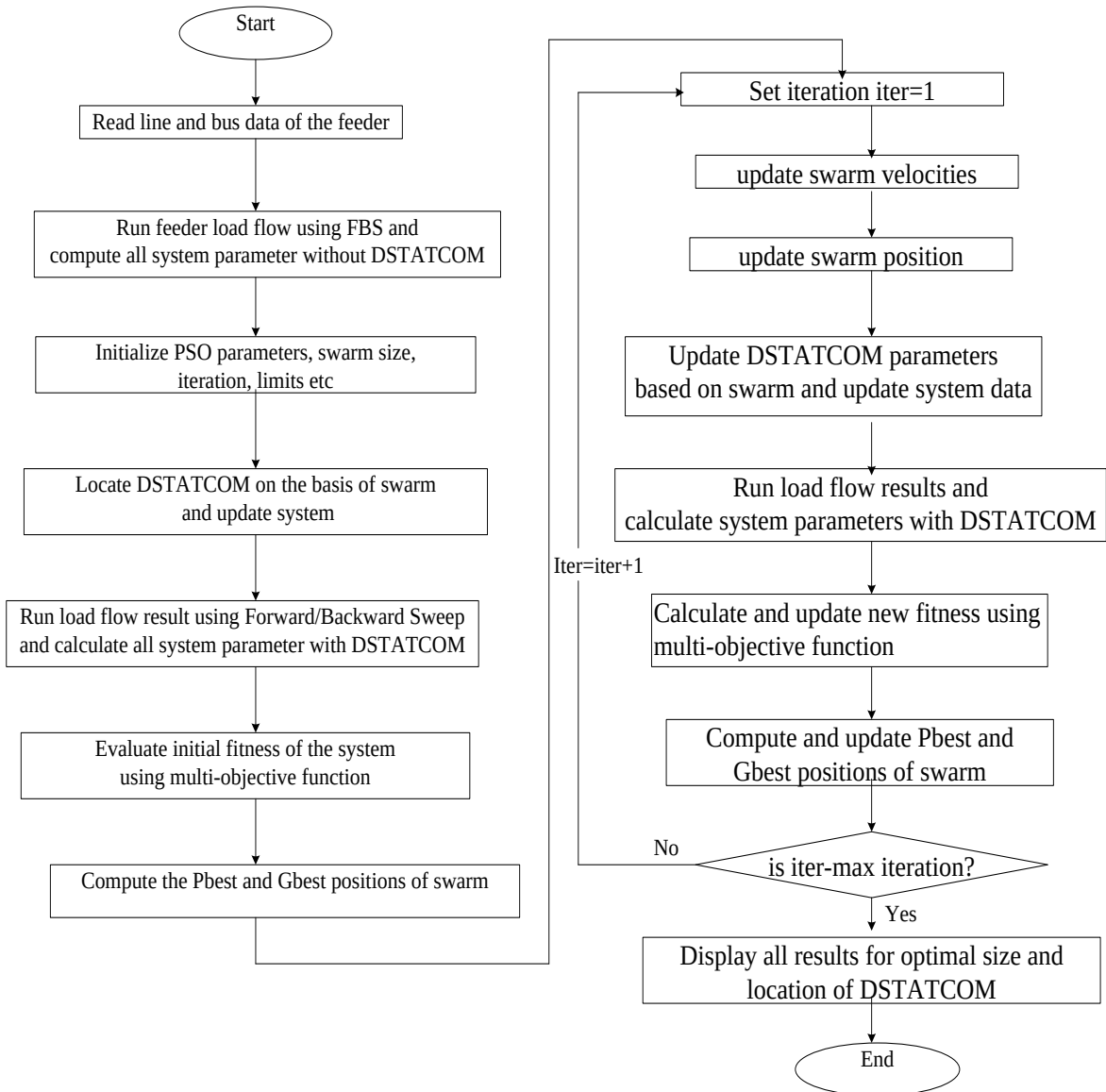
$I = 1, 2, 3 \dots n$ & $d = 1, 2, 3 \dots D$

Step 7: Iteration updating: Update the iteration counter, iter = iter+1.

Step 8: If stopping criteria are satisfied to go step 7, else go Step 2.

Step 9: Stop; the most current particle generated is the PSO's optimal solution.

❖ **Flow charts of the particle swarm optimization for the entire system**



3.6 Optimal size and Location of DSTATCOM

The thesis met the overall requirements for power loss minimization, voltage profile improvement, and voltage stability, taking into account particle swarm optimization algorithms. The search space is determined by using two methods which are voltage sensitivity factor and particle swarm optimization. The first condition is the allocation of the candidate buses for optimal DSTATCOM placement by the voltage sensitivity factor. The second condition has aimed to find the best optimal DSTATCOM sizing by using PSO with the new best system. Finally, the system is supposed to achieve several constraints within the multi-objective function from a number of the distinct objective function in the power distribution system. Moreover, the algorithms are used to manage the randomly generated switching condition for DSTATCOM sizing.

3.6.1 Problem Formulation

In an optimization problem, the different objectives can be considered. Three terms are considered in the objective function in this analysis, and the optimizer is used to optimize all three terms. The study goals are to reduce active, and reactive losses, improve the voltage profile, and enhance voltage stability. Each concept is formulated separately, and the objective function is then applied to all of them, taking into account the weighting coefficients for each. The first term in the objective function is system loss which is formulated in the following sub-section.

A. Power loss

The total losses in the distribution system can be calculated as follows:

$$f_1 = \sum_{i=1}^{NBr} R_i |I_i|^2 \quad (3.1)$$

where f_1 is the first term of the objective function related to system losses, I_i is the current of line i , R_i is the resistance of i^{th} line, and NBr is the number of system branches.

$$Q_{loss} = \sum_{i=1}^{NBr} X_i |I_i|^2 \quad (3.2)$$

Where Q_{loss} is reactive power loss, X_i is the reactance of i^{th} line.

Percentage of total power loss reduction can be calculated by:

$$\% \text{ of total loss reduction} = \frac{P_{total \text{ loss}}^{without DSTATCOM} - P_{total \text{ loss}}^{with DSTATCOM}}{P_{total \text{ loss}}^{with DSTATCOM}} * 100 \quad (3.3)$$

Where $P_{total\ loss}^{with\ DSTATCOM}$ and $P_{total\ loss}^{without\ DSTATCOM}$ are the total line losses in the system with and without installation of the distribution static compensator respectively.

B. Voltage Profile enhancement

D-STATCOM can compensate reactive power and improve the voltage profile, as stated in the previous section. The following equation (3.4) is the objective function for improving voltage profile:

$$f_2 = \sum_{i=1}^{N_{Bus}} (V_{nom} - V_i)^2 \quad (3.4)$$

where f_2 is the objective function for voltage profile improvement, V_{nom} is the nominal voltage of the system which is equal to 1 p.u, V_i is the voltage of the i^{th} bus, and N_{Bus} is the number of system buses.

C. Voltage Stability Improvement

Voltage instability is a critical problem in the distribution system. In reality, voltage stability refers to the system's ability to keep all bus voltages within an acceptable range. The reactive power required by loads is insufficiently satisfied in weak systems, and resulting in system instability and voltage collapse. As voltage stability measures, several indices have been proposed by researchers. Some are associated with buses, and others are associated with lines [46].

In this thesis, a bus-based voltage stability index is used. The index is computed for all buses and can vary from zero to one hundred percent. Voltage instability is associated with zero, and unity is the strongest state for voltage stability. The index is determined in all buses for evaluation, and the bus with the lowest value is the weakest and most suitable bus for DSTATCOM installation. The Voltage Stability Index (VSI) for a two-bus system, as shown in Figure 3.12.

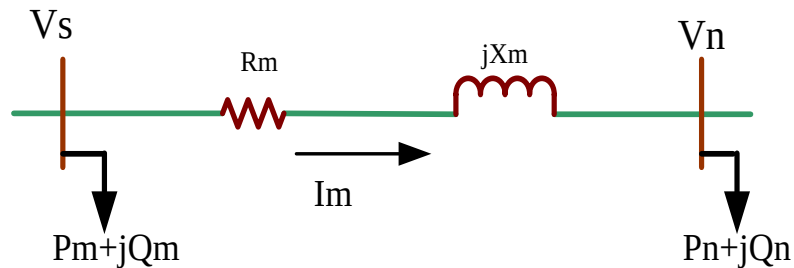


Figure 3.12 Two-bus system for VSI analysis

The voltage stability index is given as follows

$$VSI(n_2) = |V_{mi}|^4 - 4[P_{ni}(ni)R_{ni} + Q_{ni}(ni)X_{ni}]^2 - 4[P_{ni}(ni)R_{ni} + Q_{ni}(ni)X_{ni}][V_{mi}]^2 \quad (3.5)$$

where $VSI(n_2)$ is the voltage stability index at bus n_2 , mi and ni are the sending and receiving bus number, P_{ni} and Q_{ni} are active and reactive power demands at bus ni , respectively, V_{mi} is the voltage of the sending bus, R_{ni} , X_{ni} is the resistance and reactance of branch ni . Since the bus with the smallest value of VSI is the weakest bus, it determines the stability margin of the system.

$$f_3 = \min(VSI_i); i = 1, \dots, Nb$$

Considering the above-mentioned three objectives, the final objective function of the study is as follows:

$$\min\{f\} = w_1 \times f_1 + w_2 \times f_2 + w_3 \times 1/(f_3) \quad (3.6)$$

where, w_1 , w_2 , and w_3 are weighting coefficients that are determined considering the importance of the three objectives. The summation of these weighing coefficients must be equal to 1.

C. Constraints

a) DSTATCOM Constraints

❖ Number of DSTATCOM constraint

This constraint aims to reduce the number of DSTATCOM placements. As a result, the optimum number of DSTATCOM ($N_{DSTATCOM}$) must be less than or equal to the maximum number of locations ($N_{DSTATCOM}^{max}$), as follows:

$$N_{DSTATCOM} \leq N_{DSTATCOM}^{max}$$

❖ D-STATCOM Size constraints

The size of the distribution static compensator should not be either small or too large concerning the load value to achieve the appropriate solution. The reactive power injected by D-STATCOM to the system is limited by lower and upper bounds as given in the following:

$$Q_{min} \leq Q_{D-STATCOM} \leq Q_{max}$$

❖ Total reactive power constraint

The total reactive power injection ($Q_{DSTATCOM}^{Total}$) must be less than or equal the total load reactive power (Q_L^{Total}) as:

$$Q_{DSTATCOM}^{Total} \leq Q_L^{Total}$$

b) operational constraints

❖ Bus voltage constraint

All buses' system voltages should be within acceptable limits.

$$V_{min} \leq V_i \leq V_{max}$$

$$0.95 \leq V_i \leq 1.05$$

V_i is the voltage of i^{th} bus and i varies from 1 to the number of system buses.

❖ **Load rating constraint**

The load rating(current) should be less than or equal to the maximum rating.

$$I_{ij} \leq I_{ijmax}$$

❖ **Power flow constraints**

The power flow through the lines is limited by the thermal capacity of lines

$$S_{ij} \leq S_{ijmax}$$

where S_{ijmax} is the maximum capacity of the line between bus i and bus j .

The power flow through the line is limited to $S_{ijmax}=100\text{MVA}$

❖ **Active power losses constraint**

The active power loss after installation of distribution static compensator should be less than or equal to the active power loss before integration of distribution static compensator.

$$P_{total\ loss}^{withDSTATCOM} \leq P_{total\ loss}^{withoutDSTATCOM}$$

3.6.2 Energy Loss Cost, Investment Cost, and Total Annual Cost Saving

One of the objectives of the thesis work is doing the cost-effectiveness of the device which is related to system power losses. The cost analysis of the work includes the cost of DSTATCOM, cost of energy loss, and total annual cost saving with payback period and discuss as follows.

❖ **Cost of Energy Loss**

The cost of energy loss has been determined by using equation

$$CEL = (Total\ Active\ Power\ Loss) * (E_c * T)\$$$

Where E_c is energy rate (\$/kWh), T is time duration(h), $E_c=0.06\$/\text{kWh}$, $T=8760\text{h}$

❖ **Cost of DSTATCOM**

As reactive support has been identified as an important supplementary service, the devices that provide it can be compensated for their reactive support. The fee can be required to pay to the devices based on the cost savings realized as a result of DSTATCOM's loss reduction. The following equation has been employed to calculate the cost of reactive power supported by the DSTATCOM [48].

The investment cost per year can be calculated by using

$$DSTATCOM_{cost,year} = DSTATCOM_{cost} \frac{(1+B)^{nDSTATCOM} * B}{(1+B)^{nDSTATCOM} - 1}$$

Where, $DSTATCOM_{cost,year}$ is the annual cost of DSTATCOM, $DSTATCOM_{cost}$ is the cost of investment in the year of allocation(\$/KVar), B is the asset rate of return; $nDSTATCOM$ is the longevity of DSTATCOM, $Investment_{cost}=DSTATCOM_{cost}=50\$/kVar$, $B=0.1$, $nDSTATCOM=30years$

❖ Total Annual Cost Saving

The total cost saving of DSTATCOM is the difference between total energy loss cost before installation and total energy loss cost and annual DSTATCOM after installation and given by equation[44].

$$Tcs = kp(T * P_{Tloss}) - kp(T * P_{loss}^{wth DSTATCOM}) - (kc * DSTATCOM_{cost,year})$$

Where, kp, kc, T indicates the cost of energy losses, time duration proportion, and hour per year respectively. P_{Tloss} is total power loss before installation of DSTATCOM.

$P_{loss}^{wth DSTATCOM}$ is the total losses after integration of DSTATCOM. The payback back period is the ratio of the capital cost to the saving cost as shown below.

$$payback\ period = \frac{capital\ cost}{saving\ cost}$$

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

The Sabbata-I substation has fifteen feeders amongst them feeder-12 has been chosen as a case study because of its vulnerability to power interruption due to overloading which leads the line to weak voltage profile and power loss. The feeder is a medium-scale radial distribution system that has 88 branches, 89 buses, a nominal voltage of 15KV, and the total active and reactive powers are 9.588MW and 7.145MVA_r respectively. The single-line diagram of the feeder is shown in figure 3.4. All data of the feeder are shown in Appendix-A, B, and C while its line and bus data are illustrated in table 3.6.

In this chapter, simulation results are carried out and analyses of the results are presented. Two cases have been considered to analyze the effectiveness of the suggested method include the system with integration of DSTATCOM and without DSTATCOM. Power flow analysis is carried out to study the power loss, the associated cost, voltage profile, voltage stability with and without installation of D-STATCOM into the system. Further, the cost-benefit analysis has been presented at the end of this chapter. The optimization procedure has been implemented in the MATLAB 15a Software environment.

To execute the forward/backward power flow program appropriately, the maximum and minimum voltage limits have been taken as 1.05pu and 0.95pu respectively, whereas the base value was 15kV and 100MVA. The load rating for power flow analysis was 100A. The voltage Stability index has been used to find out the candidate buses for DSTATCOM placement. The potential buses are selected by particle swarm optimization in the MATLAB program environment. These candidate buses together with different distributed static compensator values have been used as an input to find out optimal DSTATCOM size, while the distributed static compensator size is considered in the range of 10KVA_r to 1200KVA_r. The first bus is taken into account as the bus of the electric power supply network when the subsequent buses of the radial distribution feeder except the reference buses are taken into consideration for the allocation of a distributed static compensator of the provided size from the range considered. To get the total objective function, the particle swarm optimization algorithm is executed with the maximum and minimum limits of distributed static compensator size, while reference voltage($V_{ref}=1$) value has been taken to evaluate the voltage profile index of the system.

4.2 Method for the Simulation Result.

Power flow analysis is the primary method used in power system studies to evaluate the existing system's status. The planning and operation of a power system require such a computation method to evaluate the steady-state performance of the power system under different working conditions and to consider the impact of change in equipment configuration. power flow solutions produced for these reasons were analyzed using a computer program. The fundamental aim of load flow performance is to generate the load power utilization at all buses of electric power systems and power at every line segment. In this section, the active and reactive power flow, power loss, each bus voltage profile, and voltage stability index of the selected feeder have been evaluated. The optimal placement and size of the distributed static compensator have been determined by applying the particle swarm optimization algorithm based on the calculated system parameters in the base case, and the outcome of the optimization has been discussed in this section. In this thesis work, the backward forward power flow method has been used for the selected line while the particle swarm optimization algorithm is used to determine the optimal size and placement of DSTATCOM in the selected radial distribution system.

4.3 The simulation Result before integration of DSTATCOM

4.3.1 Base Case Active Power Loss Simulation Result

To know the current status of the feeder the load flow analysis has been applied using forward-backward power flow methods and the active and reactive power loss was computed before mitigation of distribution static compensator on the feeder. Then, from the simulation result, the active and reactive power loss before integration of DSTATCOM became 403.0803kW and 356.1287kVAr respectively. The feeder has a huge amount of losses, consequently, \$211,859.01 per year is wasted. In a distribution system, the power loss should be minimum to maintain the system condition appropriately and the feeder requires a significant improvement to minimize the existing losses. The active and reactive power loss values in each line segment of the selected feeder are listed in the following table 4.1.

Table 4.1 base case active and reactive feeder loss simulation result

From bus	To bus	P_{loss}(KW)	Q_{loss}(KVAr)	From bus	To bus	P_{loss}(KW)	Q_{loss}(KVAr)
1	2	28.2134	29.142	46	47	0.8632	0.3251
2	3	0.09637	0.0568	47	48	0.1949	0.1149
3	4	0.01304	0.0076	48	49	0.0274	0.0161
2	5	0	0	49	50	0.0100	0.00592

2	6	4.3204	4.4617	47	51	0.3319	0.1264
6	7	0	0	51	52	0.0197	0.01164
6	8	113.33	116.998	52	53	0.0155	0.0091
8	9	0.5866	0.3458	53	54	0	0
9	10	0.3444	0.20292	42	55	1.4060	6.7908
10	11	0.0864	0.0509	55	56	0.1026	0.0605
11	12	0.0384	0.0226	56	57	0.0422	0.0249
10	13	0.0406	0.01545	55	58	0.4650	0.5317
13	14	0	0	58	59	2.3120	2.3846
8	15	10.983	11.3433	59	60	2.188	2.2599
15	16	0.0439	0.0259	60	61	0.3203	0.3309
16	17	0	0	61	62	0.0082	0.0048
15	18	34.679	35.8150	61	63	3.6400	2.1431
18	19	0.3884	0.2290	63	64	0.8339	0.4919
19	20	0.4857	0.2860	64	65	0	0
20	21	44.606	26.305	64	66	3.54534	2.0915
21	22	25.043	14.7689	66	67	0.4377	0.2546
22	23	0.059	0.03484	67	68	0.1991	0.1175
23	24	0.0336	0.01984	68	69	0	0
24	25	0.0306	0.018029	68	70	0.07332	0.0433
25	26	0.0124	0.007314	66	71	0.09438	0.0556
26	27	0.0014	0.0008297	71	72	0.0683	0.0403
24	28	0.0074	0.004367	60	73	5.1372	3.0294
28	29	0.0021	0.001251	73	74	2.5067	1.4778
22	30	7.0746	7.30732	74	75	0.1197	0.0706
30	31	28.875	29.8226	75	76	0.3931	0.2317
31	32	3.6138	3.73309	76	77	0.3706	0.1413
32	33	0.0241	0.01422	77	78	0.9136	0.3483
33	34	0	0	78	79	0.0931	0.0355
32	35	8.0813	5.3384	79	80	0.0292	0.0172
35	36	0	0	79	81	0.0067	0.0039
35	37	20.4088	21.0766	74	82	2.0476	1.2075
37	38	0.0457	0.04721	82	83	0.2734	0.16076
38	39	0.00780	0.0046	83	84	0.1942	0.1145
37	40	22.8930	13.4984	84	85	1.0432	0.6150
40	41	8.2471	4.8613	85	86	0.0872	0.0514
41	42	3.4078	2.01066	86	87	0.0161	0.0166
42	43	1.3005	0.49606	85	88	0.01317	0.0077
43	44	0.001	0.000367	84	89	0.0149	0.0088
43	45	4.247	1.6191				
45	46	0.9401	0.3584				

The simulation result was done in both tabular and graph form and the summation of all line segments is computed. Therefore, the following figure 4.1 depicts the active power loss in each of 88 branches before the integration of the distribution static compensator.

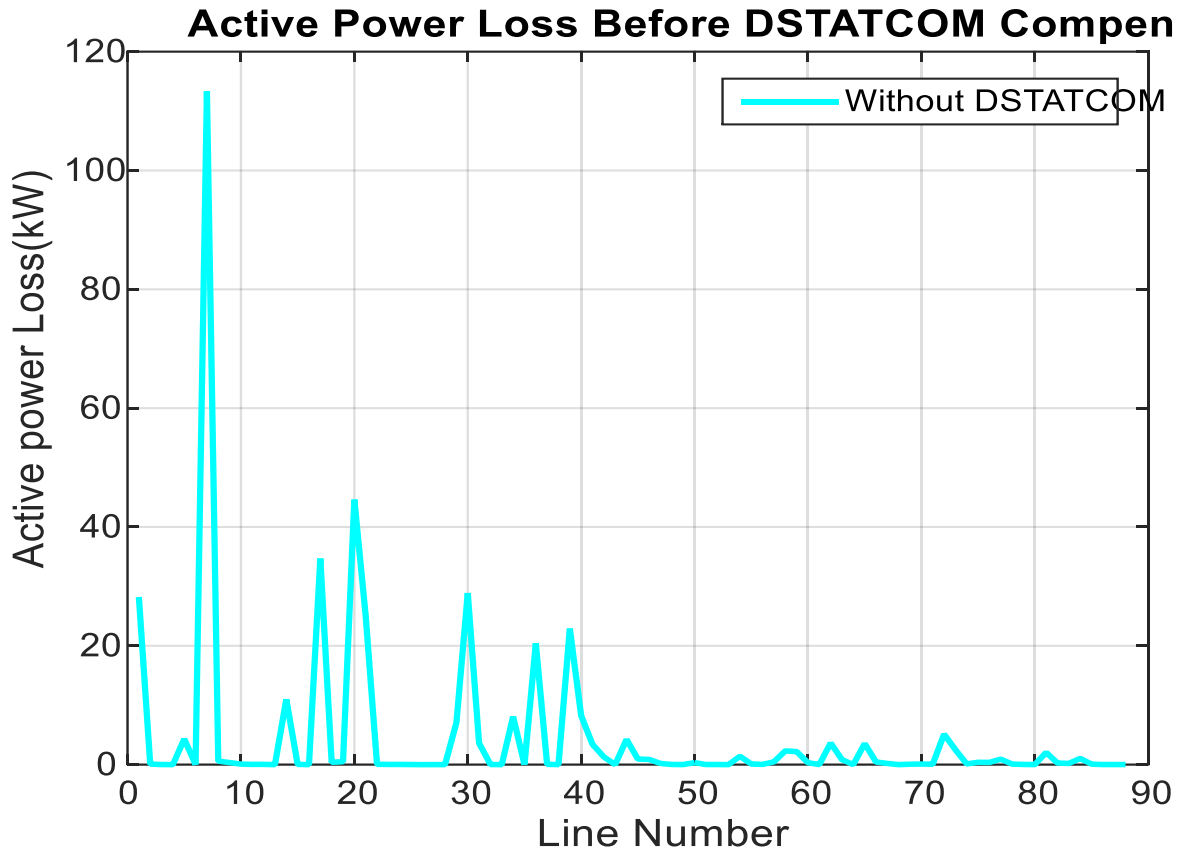


Figure 4.1 Active power loss in each branch before compensation

4.3.2 Reactive Power Loss Simulation Result Before DSTATCOM Compensation

In a power system, the need for reactive power is high on the side of a distribution system, because the majority of distribution system load demands are inductive, and it required lagging reactive power to operate in a good manner. Reactive power is essential in the distribution network to control the voltage required to provide active power through the line. Reactive power and line voltage have a direct relationship in power system technology. It's known that line voltage is used in the line to push the power through the conductor. As reactive loading of the distribution line increases the feeder voltage profile decreases. Therefore, the reactive power losses of the feeder have a great impact on the deliverance of the active power through the line and voltage profile at each bus. The following figure 4.2 illustrates the reactive power loss in each line segment of sabbata-I substation, feeder-12. The simulation result is found with the aid of applying the forward/backward load flow method before the installation of the distribution static compensator. As a result, the total

reactive power is 356.1287kVAr. This reactive loss should be reduced to maintain the system within good operating conditions. In this thesis work, the reactive power losses that occur in the system have been minimized through a reactive power compensator.

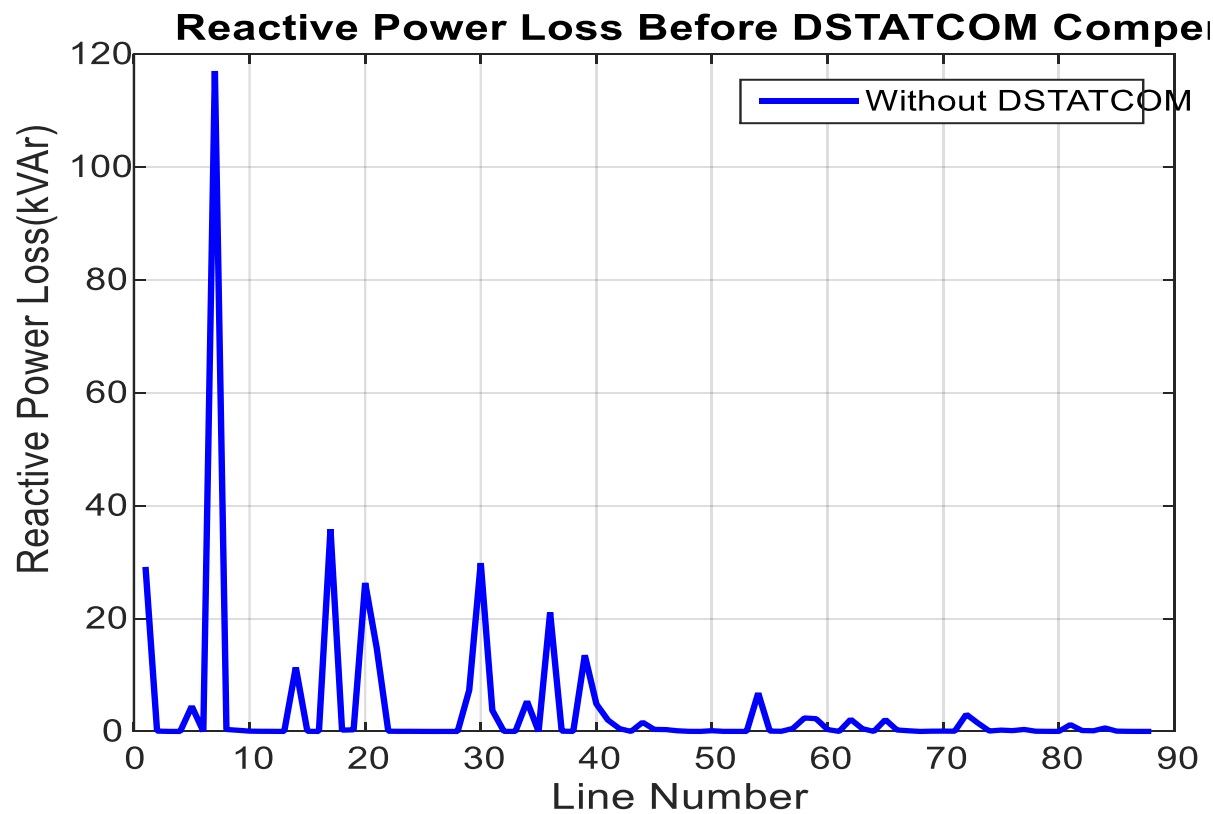


Figure 4.2 Reactive power loss in each branch without DSTATCOM

4.3.3 Voltage Profile Simulation Result Before DSTATCOM Compensation

The base case voltage profile at each bus of the feeder is also determined by utilizing the forward-backward load flow method before DSTATCOM integration and its value is listed in the following table 4.2. The minimum voltage value is 0.9357 at bus 70. As the voltage value shows in the table, the voltage profile of the feeder is depending on the distance covered and the loading of the line. As it can be seen that the voltage drops increase when the length of the feeder is more get longer. The voltage profile of the buses near the substation is high whereas the bus voltage value away from the source is less. The obtained voltage magnitudes need some improvement to have more power flow capability in the feeder. From a power system point of view, for a distribution system network, the voltage profile should be better and must be in the distribution system voltage standard level. Improving the distribution system voltage profile makes the system losses reduction and enhances the system performance. The optimal size and location of DSTATCOM on the feeder can increase the voltage profile at the required level.

Table 4.2 Base Case Voltage profile

Bus No.	Voltage profile	Bus No.	Voltage profile	Bus No.	Voltage profile	Bus No.	Voltage Profile
1	1	24	0.9684	47	0.9435	70	0.9357
2	0.9968	25	0.9683	48	0.9430	71	0.9378
3	0.9964	26	0.9682	49	0.9429	72	0.9375
4	0.9963	27	0.9682	50	0.9427	73	0.9457
5	0.9968	28	0.9683	51	0.9424	74	0.9446
6	0.9962	29	0.9683	52	0.9424	75	0.9445
7	0.9962	30	0.9674	53	0.9423	76	0.9440
8	0.98287	31	0.9628	54	0.9423	77	0.9434
9	0.982	32	0.9622	55	0.9495	78	0.9420
10	0.9816	33	0.9621	56	0.9490	79	0.9418
11	0.9813	34	0.9621	57	0.9487	80	0.9417
12	0.9810	35	0.9610	58	0.9493	81	0.9418
13	0.98147	36	0.9610	59	0.9485	82	0.9432
14	0.9814	37	0.9569	60	0.9478	83	0.9428
15	0.9814	38	0.9567	61	0.9475	84	0.9426
16	0.9811	39	0.9566	62	0.9474	85	0.9407
17	0.9811	40	0.9527	63	0.9440	86	0.9405
18	0.9767	41	0.9512	64	0.9430	87	0.9404
19	0.9760	42	0.9506	65	0.9430	88	0.9406
20	0.9749	43	0.9495	66	0.9381	89	0.9425
21	0.9715	44	0.9495	67	0.9368		
22	0.9685	45	0.9454	68	0.9361		
23	0.9684	46	0.9444	69	0.9361		

The simulation result showed the following structure after executing the power flow analysis approach, as shown in figure 4.3 below.

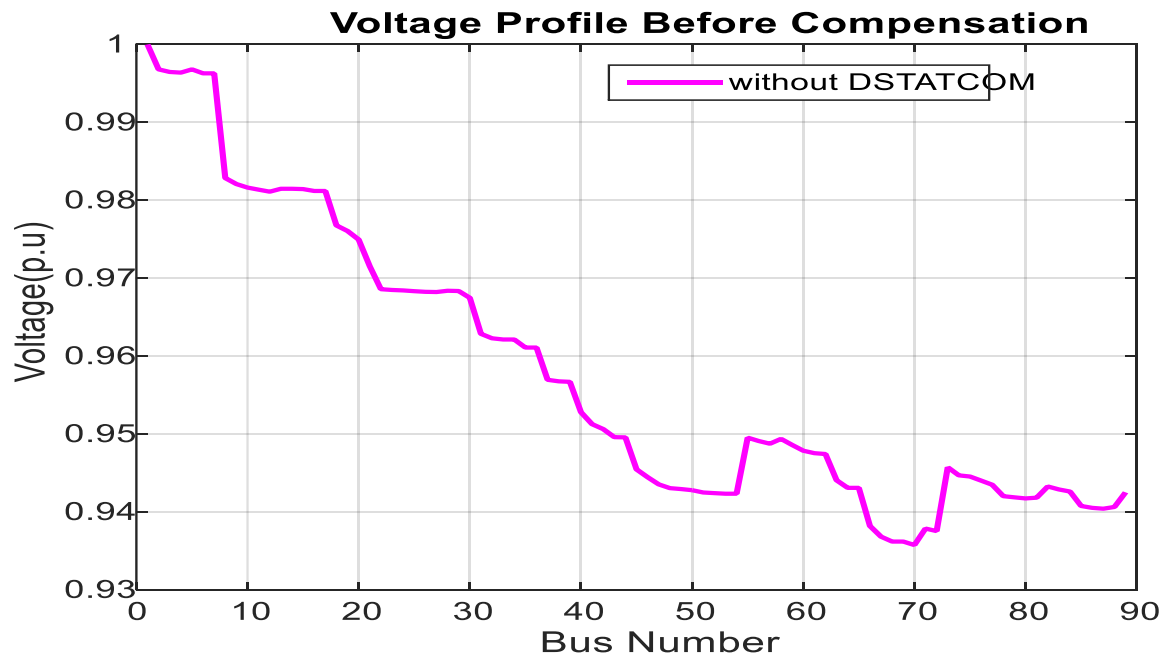


Figure 4.3 Base Case Voltage profile of the selected feeder without compensation

4.3.4 Voltage Stability Simulation Result Before DSTATCOM Compensation

In power system studies, voltage stability is a very important concern that should be considered. Knowing stability index helps the operator to have some information about whether the system is operating in a good manner or not. It ensures steady load operation and acceptable voltage levels throughout the system buses. The voltage stability index value is determined by the power flow analysis method before the installation of the distribution static compensator on the feeder. The calculated voltage stability index for all buses can vary between zero and unity. The stability of the system voltage is determined by the calculated voltage stability index. The value associated with unity is the best condition whereas the index value approaches zero shows the voltage instability of the base case. As a result, the minimum voltage stability index of the feeder is 0.7667 at bus 70. This value needs improvement and also overall value should improve across buses of the feeder. This action can be done by installing a reactive power compensator on the feeder to have a more stable system. The following table 4.3 depicts the voltage stability index of the feeder at each bus.

Table 4.3 Base Case Voltage Stability Index

Bus No.	Voltage stability	Bus No.	Voltage stability	Bus No.	Voltage stability	Bus No.	Voltage stability
1	1	24	0.8796	47	0.7925	70	0.7667
2	0.987	25	0.8792	48	0.7909	71	0.7737
3	0.9860	26	0.8789	49	0.7905	72	0.7726
4	0.9856	27	0.8788	50	0.7900	73	0.800
5	0.9873	28	0.8794	51	0.7891	74	0.7964
6	0.9852	29	0.8793	52	0.7888	75	0.7959
7	0.9852	30	0.8761	53	0.7885	76	0.7942
8	0.9332	31	0.8595	54	0.7885	77	0.7924
9	0.9302	32	0.8574	55	0.8129	78	0.7875
10	0.9285	33	0.8569	56	0.8114	79	0.7870
11	0.9275	34	0.8569	57	0.8102	80	0.7865
12	0.9265	35	0.8532	58	0.8123	81	0.7668
13	0.9279	36	0.8532	59	0.8097	82	0.7916
14	0.9279	37	0.8389	60	0.8072	83	0.7904
15	0.9278	38	0.8379	61	0.8061	84	0.7895
16	0.9269	39	0.8377	62	0.8057	85	0.7833
17	0.9103	40	0.8241	63	0.7943	86	0.7825
18	0.9076	41	0.8188	64	0.7910	87	0.7821
19	0.9076	42	0.8167	65	0.7910	88	0.7829
20	0.9035	43	0.8131	66	0.7748	89	0.7891
21	0.8909	44	0.8130	67	0.7702		
22	0.8801	45	0.7990	68	0.7682		
23	0.8798	46	0.7956	69	0.7682		

As discussed in the above section, the base case feeder has been suffered from a huge power loss that can cause voltage instability in the system. Knowing the current status of the voltage stability index helps to give a solution to how close the system is to collapse. Therefore, the simulation result shows all voltage stability indices throughout all the feeder buses and it helps the optimizer to find the most sensitive node to place the device optimally. The most sensitive buses prefer to allocate the DSTATCOM because the voltage collapse begins at that node and then spread out to other neighboring nodes. As it can be observed from a simulation result, as the feeder distance increase from a substation, the voltage drop also increases and is consequently sensitive to voltage collapse. The following figure 4.4 illustrates the voltage stability index simulation result before installation of distribution static compensator on the feeder.

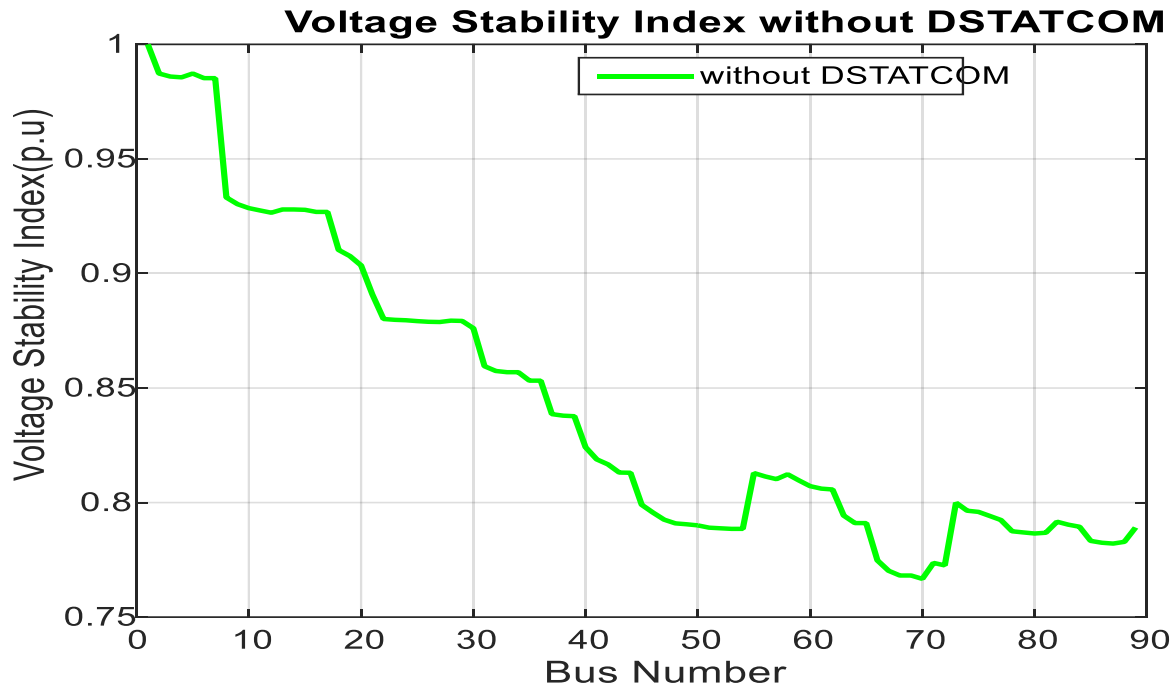


Figure 4.4 Base Case Result Voltage profile of the selected feeder without compensation

The following table 4.4 shows the overall simulation result of the base case study before the installation of the distribution static compensator. The total summation of active and reactive power losses in each line segment, minimum voltage profile, and voltage stability index calculated in all buses after executing the power flow analysis method is summarized as follows.

Table 4.4 Base Case simulation result summary

Parameters	Base case result summary
Total active power loss(kW)	403.0803

Total reactive power loss(kVAr)	356.1257
Minimum voltage(p.u)	0.9357
Minimum stability voltage index(p.u)	0.7667
Total annual energy loss(kWh)	3,530,983.43
The total annual cost of energy loss	\$211,859.0057

4.4 The Simulation Result with Distribution Static Compensator

The thesis work deals with the effects of Distributed Static Compensator integration on radial distribution lines to make a change on the line losses, voltage profile of each bus system, and voltage stability index. Analyzing both active and reactive power losses, improving the voltage profile and voltage stability of the feeder has been done in this case depending on the number and size of the penetrated device. Two factors limited the number of DSTATCOM to integrate for the selected feeder to achieve a more improved settled goal. The economic factor and unexpected effects of distribution system parameters. As the objective of the thesis express, it was mainly concerned with improving distribution line performance specifically focus on minimization of the power loss and enhancing of voltage profile, voltage stability at each bus of the feeder and the impact of distribution static compensator also evaluated. This all investigation being on the Sabbata-I substation outgoing feeder by having all information of the selected feeder including line data (resistance and reactance) and bus data (active and reactive power) etc. as discussed in chapter three at data collected and analyzed level.

4.4.1 Active Power Loss with Integration of DSTATCOM

After installation of DSTATCOM in the feeder, the base case the active power loss has been reduced from 403.0803KW to 334.2578KW which means the amount of minimized loss, in this case, became 68.8225kW and the active power loss percentage reduction becomes 21% when the device was optimally sized and allocated in the appropriate bus.

The size and location of the device have been determined by a particle swarm optimization algorithm, whereas the optimized size, and placement are 1103.42kVAr, and at bus 76 respectively. The saved power loss could not be taken as a small value because it can run a huge machine that can manufacture different things to fulfill social needs. Especially in a developing country like Ethiopia, the saved power has very important to improve the current economic status. Therefore, due to the energy saved the 55,872.5\$ amount of cost can be saved from one feeder only. The reduced loss can make the feeder more reliable to the customer by reducing the interruption frequency and duration.

The real power losses of the existing feeder with one DSTATCOM are shown in Figures 4.5. It can be noted that the real power losses have been minimized across all line segments.

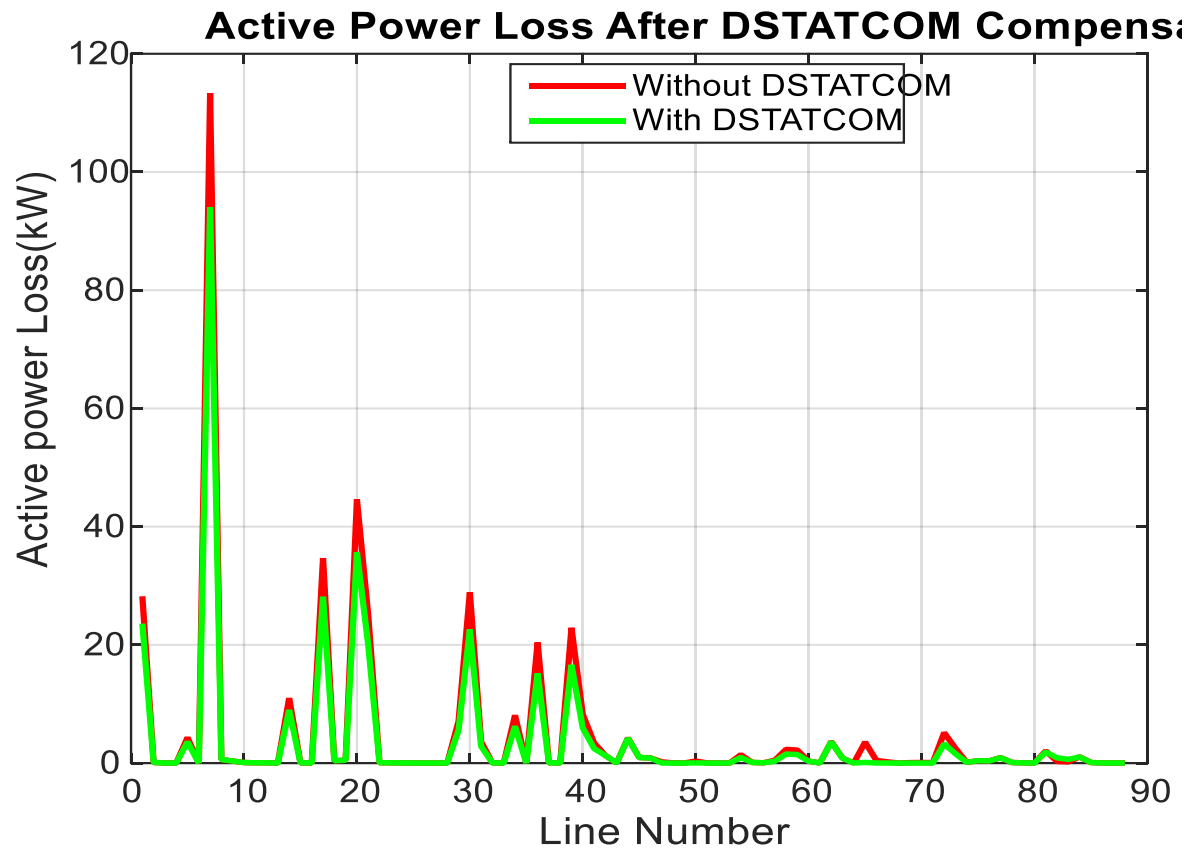


Figure 4.5 Active power loss after integration of DSTATCOM

The total active power loss of the feeder with and without distributed static compensator is shown in figure 4.6 below. It can be seen that the sum of the feeder loss in each line segment after installation of DSTATCOM is less than the base case losses.

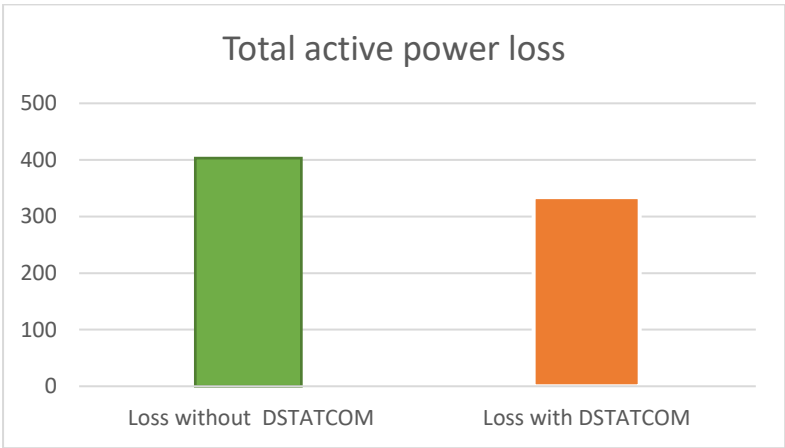


Figure 4.6 total power loss with and without DSTATCOM

It can be observed that after the installation of the distribution static compensator the active power losses have significantly reduced.

4.4.2 Reactive Power Loss with DSTATCOM Allocation

Maintaining voltage magnitude in the distribution system is very important for the proper operation of the existing system to reduce losses and to control the capability of the system to withstand and avoid voltage collapse. Reactive power is significantly related to the operating voltage, as a result, insufficient reactive power causes the voltage to a minimum level while sufficient reactive power causes enhancing voltage profile in the system. Therefore, reactive power loss in the feeder can reduce the voltage levels and it is difficult to travel the power required by loads through the feeder. Thus, the reactive power loss should be minimized as much as possible in the distribution system.

The reactive power compensator has been employed in this case and the result shows a significantly minimized reactive power loss that can keep the system in a stable state. After DSTATCOM integration in the feeder, reactive power loss has been reduced from 356.1287KVAR to 296.778KVAR and the percentage of reduction was 20%. Figure 4.7 below illustrates the reduced reactive power loss in the feeder after the installation of the distribution static compensator. Where the blue and red lines on the figure represent reactive power loss before and after DSTATCOM integration respectively.

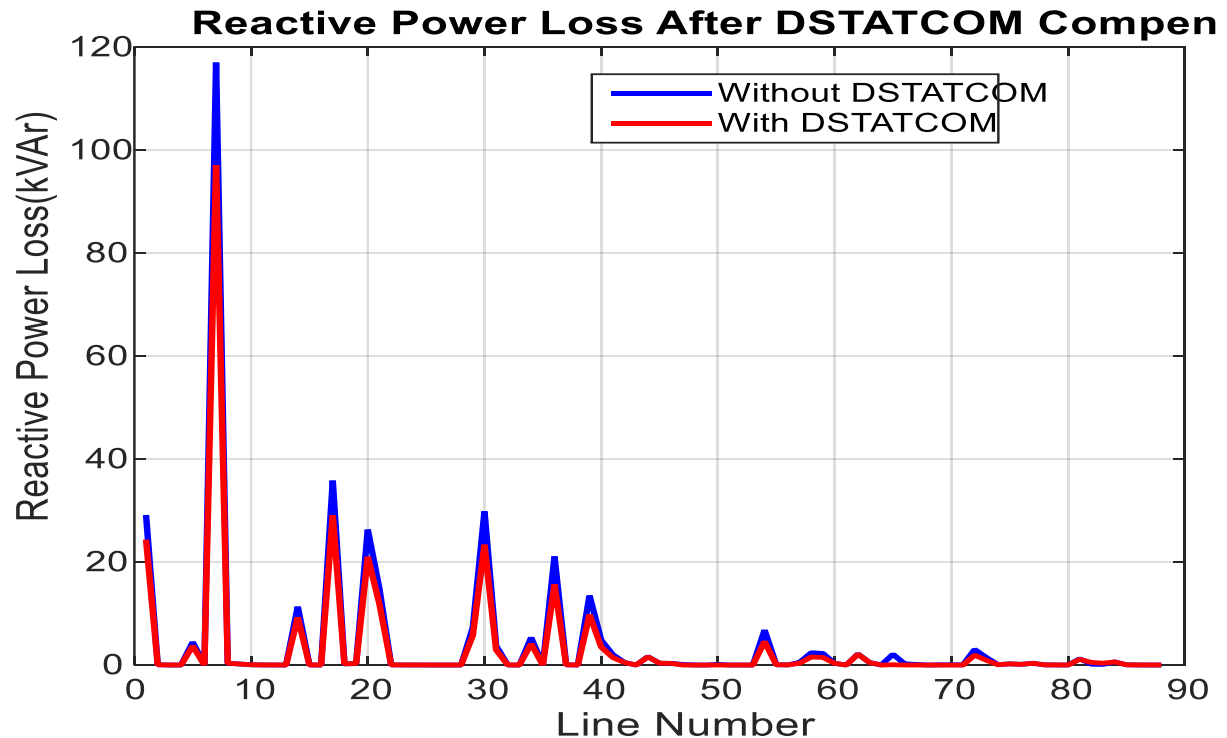


Figure 4.7 Reactive power loss after integration of DSTATCOM

The total summation of reactive power loss in the feeder with and without distributed static compensator is shown in figure 4.8 below. It can be seen that the sum of the reactive loss in each line segment after installation of DSTATCOM is less than before consideration of distribution static compensator.

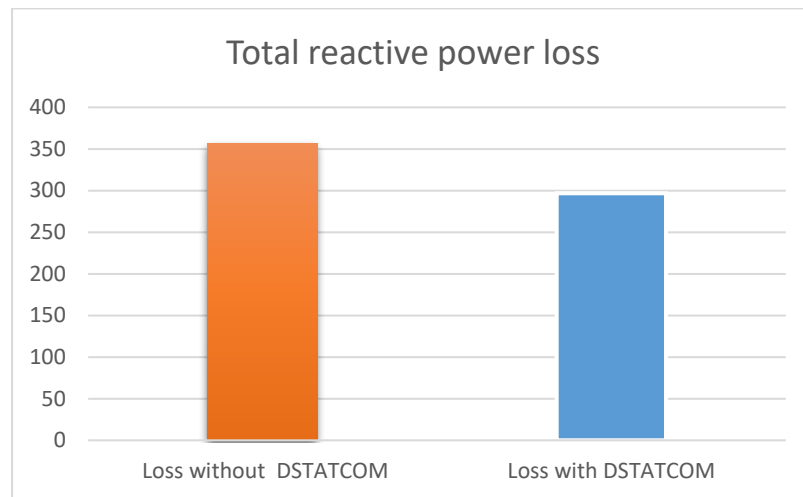


Figure 4.8 total power loss with and without DSTATCOM

The overall simulation result that is found after injection of reactive power at the appropriate place is explained in the following table 4.5 including location, size, number of DSTATCOM, active and reactive power loss, percentage reduction of active and reactive power losses, investment cost, and annual cost saving.

Table 4.5 the power loss simulation result summary after integration of DSTATCOM

Parameters	Without DSTATCOM	With DSTATCOM
Location	-----	at bus 76
Size(kVAr)	-----	1103.42kVAr
Number of DSTATCOM	-----	1
Active power loss (kW)	403.08	334.2578
Reactive power loss(kVAr)	356.1287	296.778
%reduction in active power loss	----	21
%reduction in reactive power loss	----	20
Energy Loss Cost	211,859.0057\$	155,986.5168\$
Annual cost saving	----	55,872.5\$
% of loss cost reduction	-----	35.82

4.4.3 Voltage Profile Improvement After DSTATCOM Placement

The distribution static compensator can be penetrated at the distribution feeder with the objective of power loss reduction and enhancing voltage profile by providing and absorbing sufficient reactive power to the network at the optimum location and proper size. As it can be seen from the base case system after load flow analysis has been applied, the bus system shows the weak voltage profile at some buses that have not been sufficient at the distribution system.

Before the compensation of the device, the minimum voltage value was about 0.9357 at bus 70 that almost out of the allowable voltage range as IEEE distribution system standard level. However, after the installation of the DSTATCOM at the appropriate bus by PSO, the minimum voltage profile has been improved from 0.9357 to 0.95001 at bus 70 which is better when compared to the voltage value obtained before DSTATCOM installation and also all of the bus voltage profile across the feeder has been enhanced in the required range. As it can be seen that from the voltage profile simulation result, the voltage value at bus 70 and neighboring buses are more enhanced than the other buses. The following figure 4.9 illustrates the voltage profile improvement obtained after the integration of DSTATCOM. Where the red and black line denotes the feeder voltage profile before and after installation of DSTATCOM respectively.

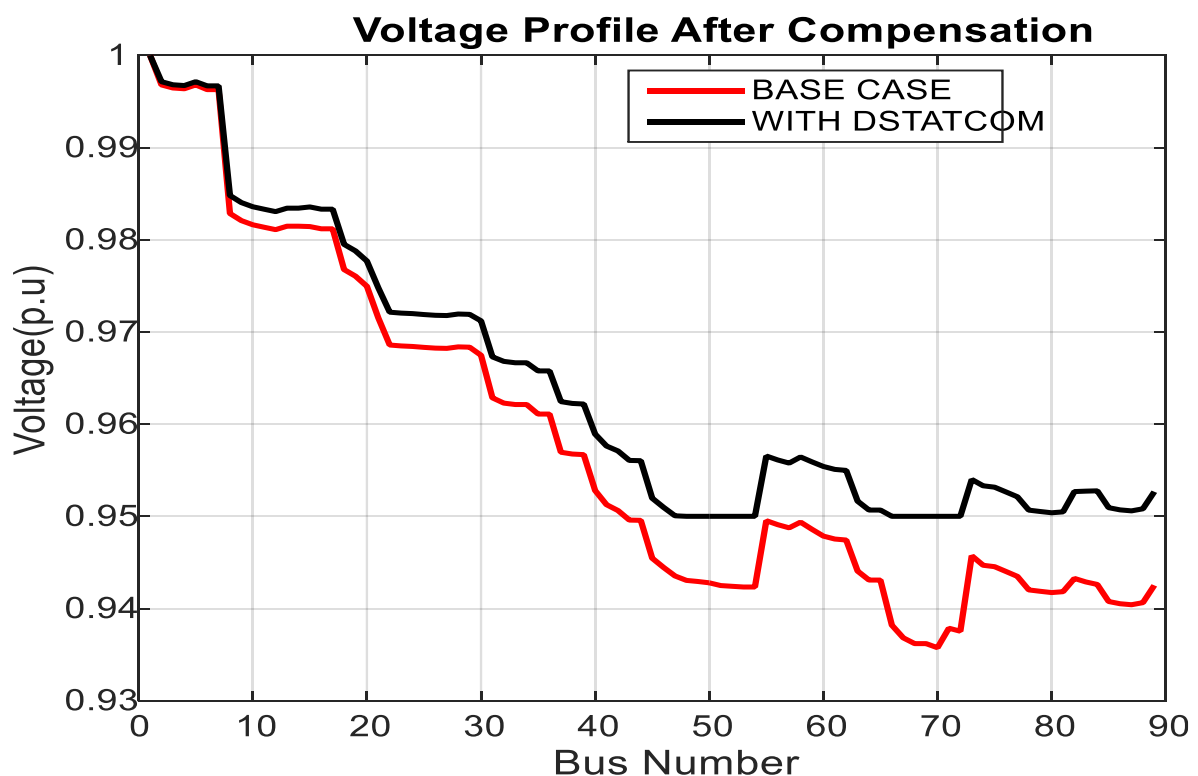


Figure 4.9 Voltage Profile After DSTATCOM Placement

4.4.4 Voltage Stability with DSTATCOM Installation

The main important thing in a distribution system is the capability of the system to return to its equilibrium operating state after being subjected to some disturbance. The distribution system voltage stability is determined by its index, where the value of the index should be between zero and unity(one). The bus that has a voltage stability index value nearest to zero is more vulnerable to voltage collapse whereas, the value approach to unity is more stable than the other buses. The radial distribution system's voltage collapse could be caused by low voltage stability, which might cause the system to be interrupted. The voltage stability index value should be maximized as much as possible in radial distribution systems to avoid voltage collapse and to make the system more reliable.

To maintain the voltage stability index in the required range, the DSTATCOM plays a great role in the selected feeder. After determining the optimal size and placement of DSTATCOM into the feeder the result shows voltage stability improvement. As a result, the minimum voltage stability index was 0.7667 at bus 70 before installation of the distributed static compensator, however after integration of DSTATCOM the minimum voltage stability index increased to 0.8145 at bus 70, and the whole system voltage stability index improved. The index value at bus 70 and all nearby buses improve more than the other buses, as can be seen from figure 4.10.

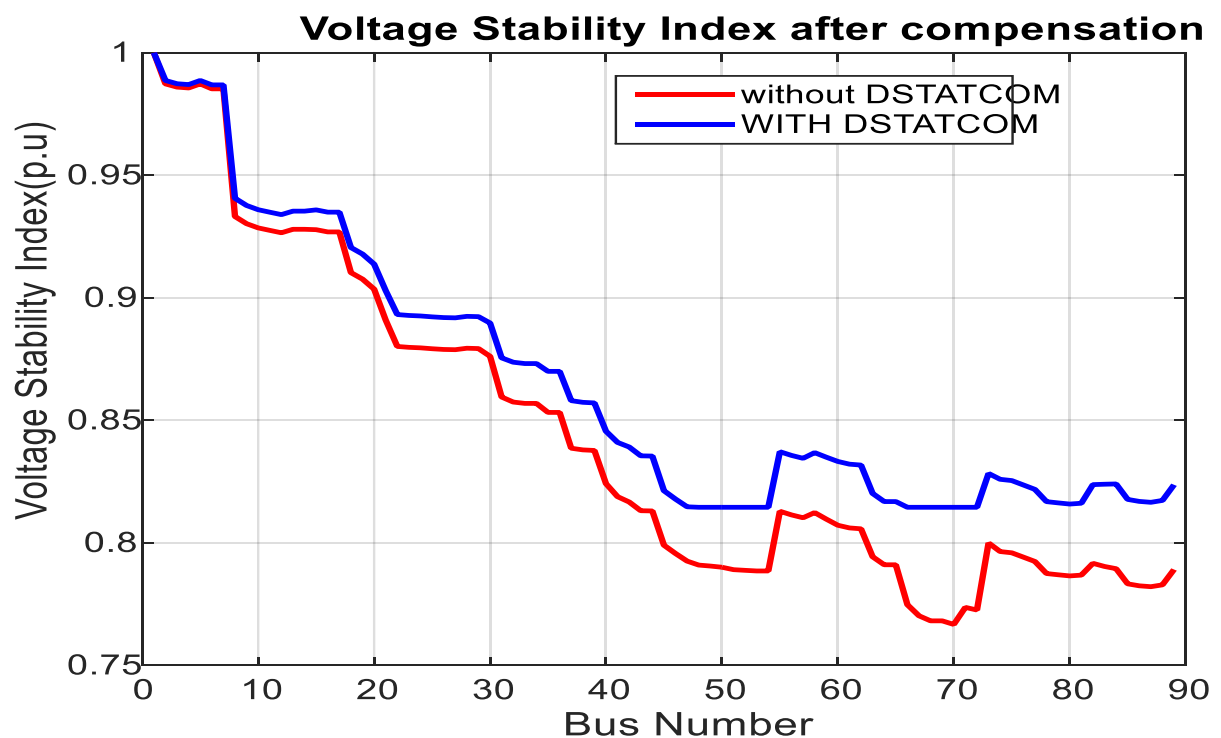


Figure 4.10 Voltage Stability Indices with DSTATCOM Compensation

The above figure 4.10 illustrates the voltage stability indices of Sabbata-I substation feeder-12 after installation of DSTATCOM. The value of the voltage stability index for all buses in the feeder before installation of distribution static compensator is observable as shown in figure 4.4 above. However, the bus voltage stability index is significantly improved after the integration of a distribution static compensator on the feeder, and the voltage stability index displayed the same characteristic as the voltage profile in the feeder

4.4.5 Total Annual Cost Saving After Installation of DSTATCOM

The cost-effectiveness of distributed static compensator integration on the existing feeder is calculated from the difference between total energy loss cost before installation of the DSTATCOM, and the annual cost of DSTATCOM after installation that was computed by using the appropriate formula. The existing feeder's total power loss was 403.0803kW. In other words, Ethiopian Electric Utility lost 211,859.0057\$ per year only from Sabbata-I substation, feeder-12 because of the power loss existing in the feeder. However, after installation of the distribution static compensator, the power loss found on the feeder becomes 334.2578kW which means the energy lost cost is reduced to 155,986.5168\$ per year. It can be seen that 55,872.5\$ per year can be saved when the 1103.42kVAr distribution static compensator is installed in the optimum place on the feeder.

Table 4.6 cost benefits summary

parameter	Value
Loss Cost Without DSTATCOM	211,859.0057\$
Loss Cost With DSTATCOM	155,986.5168\$
Total cost saved	55,872.5\$
% of cost reduced	35.8%

The saving cost has already been estimated, whereas the capital cost of the distribution static compensator is decided by the device size and production. In this thesis work, the DSTATCOM cost per kVAr was 50\$/kVAr, the total DSTATCOM cost 55,171\$, while the installation fee was \$1,000. By adding DSTATCOM and the installation cost, the total capital cost yield was 56,171\$, When the saving and capital costs are substituted in the payback formula, the payback period is reduced to about one year. This suggests that after one year, when the distribution static compensator is placed into the Sabbata-I distribution substation, feeder-12, 55,872.5\$ per year can be saved. As a result, in a radial distribution network, it is more cost-effective to supply reactive power compensating closer to the load.

4.5 Overall Discussion of the Simulation Result

As tried to discuss in the above section, the results show that the system with DSTATCOM cases has more impact on the feeder and plays a great role in minimizing active and reactive power loss, improving the voltage profile and voltage stability index across the entire system bus. It can be observed that Distribution Static Compensator has played a great role in case of cost reduction.

Table 4.7 shows the overall outcomes of the thesis work including the improvement of voltage profile, voltage stability index, percentage reduction of active and reactive power, cost benefits, location, and size of the device has been summarized and based on the obtained result, the integration of DSTATCOM into distribution line is more efficient than the base case system in terms of cost benefits, voltage profile level, voltage stability index and reducing active and reactive power loss of the feeder. In general, the outcomes from all cases are summarized and presented in the following table 4.7.

Table 4.7 summary of the simulation results

Performance measurement	Before DSTATCOM Installation	With DSTATCOM Integration
DSTATCOM Location	-----	at bus 76
DSTATCOM Size	---	1103.42kVAr
Number of DSTATCOM	---	1
Total active power loss(KW)	403.0803	334.2578
Total Reactive power Loss(KVAr)	356.1287	296.7780
Minimum voltage(PU)	0.935	0.95001
Minimum voltage stability index(PU)	0.7667	0.8145
Percentage active power reduction(%)	----	21%
% of reactive power reduction	----	20%
Total annual energy saved(kWh)	-----	602,885.1
Total annual Cost of energy loss	211,859.0057\$	\$155,986.5168
Total annual cost saving	-----	\$55,872.5
% of annual cost saving	-----	35.82%
DSTATCOM Cost	----	\$55,171
Total installation cost	-----	\$1000
Total capital cost	-----	\$56,171
Payback period	-----	1year

Therefore, if the Distribution Static Compensator integrated at Sabbata-I distribution substation on feeder-12 at bus 76, the voltage profile becomes maintained within acceptable distribution system operating voltage deviation range with a minimum voltage level of 0.950001, the minimum voltage stability index improved to 0.8145, and the active and reactive power loss also reduced by a percentage of 21% and 20% respectively. The cost-effectiveness of the thesis work is also satisfactory as it can be seen from the result value and the percentage of cost reduction was 35.82%.

❖ **The impact of obtained results in terms of power demand on the feeder.**

The feeder mainly provides electricity to various households, commercial centers, and industrial units. However, the feeder has a problem of frequent power interruption with a long duration. The customers on the feeder used electricity for different purposes for example in households for power appliances like lightning systems, for cooking, heating, and cooling system, and also for power electronics devices. They also use for a medical center and operate lifts to make movement ease, and to access social services such as education center, water supply, fabric, and railway which needs a reliable power supply to operate optimally and provide the vital service to customers. When the feeder is interrupted, all these services can be faced by power disrupted which impacts the economy, and access to social services. The frequent power interruption might cause direct damage to electrical appliances that are used by customers on the feeder. Furthermore, the lack of a consistent power supply also renders electrical appliances dismissed and unable to fulfill the intended purpose. For example, the electrical machine can not be run with its full efficiency due to an inadequate power supply.

The thesis work was to solve the problems that arise on the customer's side by supplying an uninterruptable power supply and meet their needs. The distribution static compensator has been used which can maintain the voltage magnitude at the desired value and minimizes the feeder losses by providing sufficient reactive power to satisfy the electric power demand. Thus the above problem that occurs due to power interruption has been solved by this work. Therefore, from the obtained outcomes anyone can affirm the efficiency improvement of the base case system.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

The following conclusions, recommendations, and possible future works have been made based on the obtained results with and without distributed static compensator with the objective of power loss reduction and voltage profile enhancement of the base case feeder.

5.1 Conclusion

The distribution system is always encountered some power quality problems such as high losses, maximum voltage drops, and instability of the bus voltage; hence, a technical solution must be necessary to solve the problem. In this thesis work, the optimal size and location of the Distribution Static Compensator have been utilized to solve the power quality problem that occurs in the distribution system. The forward-backward power flow method was used for load flows analysis whereas, the particle swarm optimization algorithm was employed to decide the optimal size and location of the device. The method was implemented on the Sabbata-I substation, a feeder that has 88 branches and 89 buses which are suffered from a power interruption problem due to the increase of power demand.

In this thesis, only two cases are taken into consideration to analyze the simulation result. In the first case, the system was simulated without DSTATCOM incorporation into the feeder using the forward/backward load flow method. From the simulation result, different quantities including active power loss, reactive power loss, voltage profile, and voltage stability can be known. It can be seen that the active power loss, reactive power loss, minimum voltage magnitude, and minimum voltage stability index before allocation of DSTATCOM was 403.0803kW, 356.1287kVAr, 0.9357p.u, and 0.7667p.u (at bus70) respectively. The cost wasted due to feeder loss before DSTATCOM placement was \$211,859 per year. In the second case, the optimal size and placement of DSTATCOM were integrated into the feeder using particle swarm optimization to minimize power loss, and improve voltage profile, and voltage stability. From the simulation result, the optimal size and location of the device are 1,103.42kVAr and at bus 76. As a result, the active power loss, reactive power loss, minimum voltage value, and voltage stability became 334.2578kW, 296.7780kVAr, 0.950001 p.u, and 0.8145 p.u respectively. After DSTATCOM allocation, the lost cost due to power loss was minimized to \$155,986.52 per year. The annual cost saving due to the integration of the DSTATCOM was \$55,872.5 with a one-year payback period.

The simulation result shows that installing an optimally sized and located distribution static compensator can significantly reduce the power loss, enhance the voltage profile and voltage stability of the distribution feeder. Furthermore, it reduces 21% and 20% of system active and reactive power loss respectively and improves the voltage profile to the international standard voltage deviation range, increases the voltage stability, and is also, cost-effective. Therefore, the thesis work's objectives were met, and the PSO method was shown to be an effective method for optimizing the size, and placement of distribution static compensators in the Sabbata-I substation distribution network, to minimize real and reactive power losses, enhancing voltage profile, and voltage stability.

5.2 Recommendation

The thesis work will help Ethiopian electric utility by minimizing the wastage of active and reactive power in a radial distribution network. As a result, the reduced losses will enable to fulfill the social demands and minimizes the cost wastage due to losses. In addition, the thesis work will ensure that the voltage profile and voltage stability at end-users are improved to the IEEE standard limit when DSTATCOM is integrated into the feeder. This will save money on compensation for customer equipment that has been out of function due to voltage fluctuations that are outside of permitted limits. As a result, the EEU is more cost-effective and reliable to operate. The government should install the suggested device on the distribution network to improve system performance.

This thesis work has been conducted only on the Sabbata-I substation 15kV distribution feeder-12, the next researcher can apply the same approach to any other distribution feeders to improve its performance by minimizing the feeder loss and maintaining the voltage profile. In this thesis, the objective of the work has been met with consideration of phase balanced loading condition, however phase imbalance and harmonics have not been examined. The future work would be considered phase load imbalance and harmonics. The hybrid optimization algorithm can more place and size the device optimally and the simultaneous DSTATCOM with another type of DG can improve the radial distribution system performance and It will be the focus of future study.

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Appendix A: Load demand on the Feeder

Table appendix-A: The Sample of monthly peak and minimum load of Sabbata-I substation outgoing feeder.

January 2020

Bay/line	Peak load						Minimum load					
	Power MW	Current (A)			Time	Date	Power (MW)	Current (A)			Time hour	Date
		R	S	T				R	S	T		
F1	14.07	591	591	591	19:00	6/1/2020	2.05	86	86	86	3:00	1/1/2020
F2	12.86	540	540	540	9:00	11/1/20	1.71	72	72	72	0:00	1/1/2020
F3	10.29	432	432	432	20:00	6/1/2020	1.67	70	70	70	3:00	7/1/2020
F4	14.12	593	593	593	19:00	6/1/2020	1.83	77	77	77	1:00	10/1/20
F5	1.45	61	61	61	16:00	17/01/20	0.09	4	4	4	15:00	11/1/20
F6	0.71	30	30	30	9:00	17/01/20	0.24	10	10	10	3:00	9/1/2020
F7	8.5	357	357	357	14:00	9/1/2020	0.90	38	38	38	2:00	21/1/20
F8	4.69	197	197	197	20:00	11/1/20	0.83	35	35	35	3:00	18/1/20
F9	6.5	273	273	273	11:00	31/01/20	0.62	26	26	26	0:00	7/1/2020
F10	6.24	262	262	262	11:00	20/01/20	0.95	40	40	40	3:00	8/1/2020
F11	10.05	422	422	422	13:00	29/01/20	1.95	82	82	82	2:00	6/1/2020
F12	11.4	479	479	479	20:00	6/1/2020	2.26	95	95	95	2:00	8/1/2020
F13	13.1	163	163	163	19:00	6/1/2020	0.71	30	30	30	2:00	1/1/2020
F14	2.29	96	96	96	18:00	1/1/2020	0.43	18	18	18	1:00	7/1/2020
F15	12.02	505	505	505	20:00	12/1/20	0.76	32	32	32	2:00	24/01/20

March 2020

F1	14.6	611	611	611	19:00	16/03/20	2.30	98	98	98	3:00	13/3/20
F2	13.9	584	584	584	11:00	20/3/20	0.02	1	1	1	15:00	5/3/2020
F3	10.9	460	460	460	19:00	28/3/20	1.80	45	45	45	15:00	1/3/2020
F4	15.5	655	655	655	19:00	17/3/20	2.60	62	62	62	3:00	17/3/20
F5	1.5	65	65	65	16:00	17/3/20	0.04	2	2	2	20:00	5/3/2020
F6	0.9	37	37	37	9:00	23/3/20	0.04	2	2	2	2:00	6/3/2020
F7	8.3	350	350	350	11:00	21/3/20	0.80	34	34	34	15:00	21/3/20
F8	3.6	154	154	154	13:00	22/3/20	0.60	27	27	27	3:00	15/3/20
F9	7.1	299	299	299	10:00	16/3/20	0.70	30	30	30	3:00	9/3/2020
F10	6.4	270	270	270	20:00	16/3/20	1.30	55	55	55	3:00	18/3/20
F11	10.9	458	458	458	12:00	18/3/20	1.70	72	72	72	3:00	9/3/2020
F12	11.1	466	466	466	13:00	21/3/20	0.60	28	28	28	2:00	17/3/20
F13	4.5	190	190	190	9:00	9/3/2020	0.60	28	28	28	3:00	9/3/2020
F14	2.3	98	98	98	10:00	17/3/20	0.40	18	18	18	10:00	18/3/20
F15	11.5	482	482	482	12:00	27/3/20	0.95	40	40	40	4:00	23/3/20

May 2020

F1	5.9	248	248	248	11:00	20/5/20	0.30	12	12	12	2:00	20/5/20
F2	12.6	532	532	532	11:00	8/5/2020	0.02	1	1	1	12:00	21/5/20
F3	10.8	454	454	454	20:00	27/05/20	0.90	40	40	40	18:00	13/5/20
F4	16.4	688	688	688	18:00	22/05/20	1.90	80	80	80	4:00	11/5/2020

F5	1.6	67	67	67	10:00	16/05/20	0.02	1	1	1	3:00	17/5/20
F6	0.7	29	29	29	10:00	28/05/20	0.07	3	3	3	11:00	3/5/2020
F7	9.2	389	389	389	15:00	3/5/2020	1.02	43	43	43	11:00	3/5/2020
F8	5.6	236	236	236	14:00	2/5/2020	0.04	2	2	2	2:00	30/5/20
F9	8.1	340	340	340	16:00	8/5/2020	0.70	31	31	31	3:00	18/5/20
F10	6.8	288	288	288	16:00	4/5/2020	0.80	34	34	34	4:00	7/5/2020
F11	10.7	452	452	452	16:00	4/5/2020	1.40	58	58	58	9:00	18/5/20
F12	11.8	498	498	498	18:00	18/5/20	2.02	85	85	85	3:00	13/5/20
F13	8.1	340	340	340	12:00	19/5/20	0.70	30	30	30	11:00	3/5/2020
F14	2.4	101	101	101	9:00	26/5/20	0.40	18	18	18	16:00	2/5/2020
F15	11.9	499	499	499	18:00	22/5/20	1.30	56	56	56	12:00	12/5/20

July 2020

F1	8.4	351	351	351	13:00	8/7/2020	0.80	35	35	35	1:00	18/7/20
F2	12.4	522	522	522	15:00	17/7/20	0.70	33	33	33	4:00	3/7/2020
F3	11.2	470	470	470	20:00	25/7/20	0.60	26	26	26	4:00	3/7/2020
F4	15.2	640	640	640	13:00	2/7/2020	0.20	10	10	10	11:00	25/7/20
F5	1.3	53	53	53	9:00	17/7/20	0.20	10	10	10	7:00	1/7/2020
F6	0.7	30	30	30	11:00	30/7/20	0.20	10	10	10	3:00	10/7/20
F7	9.3	390	390	390	10:00	18/7/20	0.70	28	28	28	1:00	1/7/2020
F8	5	211	211	211	13:00	13/7/20	0.60	26	26	26	4:00	3/7/2020
F9	6.8	288	288	288	10:00	17/7/20	0.30	11	11	11	4:00	3/7/2020
F10	9	380	380	380	19:00	19/7/20	0.70	28	28	28	4:00	1/7/2020
F11	11	485	485	485	10:00	10/7/20	0.80	35	35	35	2:00	1/7/2020
F12	12.2	512	512	512	12:00	13/7/20	0.20	10	10	10	1:00	4/7/2020
F13	4.3	180	180	180	19:00	22/7/20	0.60	25	25	25	2:00	4/7/2020
F14	2.4	100	100	100	18:00	25/7/20	0.20	10	10	10	22:00	13/7/20
F15	11.6	489	489	489	13:00	11/7/20	1.20	50	50	50	0:00	30/7/20

November 2020

F1	7	295	295	295	19:00	9/11/20	0.78	33	33	33	15:0	9/11/20
F2	12.7	534	534	534	9:00	12/11/20	0.12	5	5	5	15:0	2/11/20
F3	11.7	492	492	492	19:00	20/11/20	0.76	32	32	32	6:00	5/11/20
F4	15.4	648	648	648	20:00	20/11/20	1.55	65	65	65	2:00	11/11/20
F5	1.1	45	45	45	15:00	23/11/20	0.02	1	1	1	1:00	23/11/20
F6	0.95	40	40	40	13:00	16/11/20	0.09	4	4	4	3:00	20/11/20
F7	8.64	363	363	363	11:00	28/11/20	0.67	28	28	28	16:0	1/11/20
F8	5.31	223	223	223	20:00	25/11/20	0.62	26	26	26	1:00	23/11/20
F9	6.5	273	273	273	10:00	18/11/20	1.07	45	45	45	3:00	16/11/20
F10	8.8	371	371	371	19:00	9/11/20	1.31	55	55	55	3:00	2/11/20
F11	11.3	476	476	476	19:00	18/11/20	1.80	75	75	75	3:00	2/11/20
F12	11.62	488	488	488	19:00	13/11/20	2.43	102	102	102	2:00	5/11/20
F13	6.6	279	279	279	11:00	28/11/20	0.90	38	38	38	3:00	2/11/220
F14	2.4	100	100	100	18:00	12/11/20	0.40	17	17	17	9:00	28/11/20
F15	12.1	510	510	510	20:00	20/11/20	0.50	21	21	21	16:00	9/11/20

Appendix B: Power Interruption Data

Table Appendix-B: The two years (2019&2020) power interruption data

Total Interruption Data During 2019							
Feeder	Peak load MW	Cause of interruption				Total	The total duration of the interruption in (Hrs/yr)
		OL	SC	EF	UF		
		(freq.int/yr)	(freq.int/yr)	(freq.int/yr)	(freq.int/yr)	(freq.int/yr)	
F1	9.8	64	47	144	0	255	390.73
F2	12.7	84	160	340	0	584	526.71
F3	9.5	69	81	234	0	384	515.09
F4	11	61	51	76	47	235	383.03
F5	1.5	71	61	16	0	148	362.24
F6	2.6	145	49	45	0	213	485.95
F7	8.7	119	118	117	0	354	539.05
F8	2.5	75	16	36	0	127	386.77
F9	6.3	104	64	28	0	196	418.66
F10	4.1	88	35	110	0	233	515.51
F11	10.2	141	83	145	47	416	577.01
F12	11.2	145	54	142	0	339	602.31
F13	4.4	129	110	97	0	336	420.25
F14	2.3	46	9	39	0	94	48.62
F15	9.8	4	0	9	0	9	12

Total Interruption Data During 2020							
F1	7.3	33	43	87	0	163	512.95
F2	14.1	141	173	236	0	550	579.93
F3	10.8	26	132	81	0	239	216.42
F4	15.4	91	37	155	33	316	318.41
F5	8.5	95	36	42	0	173	279.56
F6	0.81	141	38	55	0	234	296.92
F7	7.5	122	133	86	0	341	563.22
F8	4	96	26	67	0	189	180.38
F9	6	75	106	30	0	211	257.57
F10	9.4	101	26	69	0	196	263.49
F11	11	140	147	151	13	451	405.8
F12	13.1	143	85	118	0	302	650.0
F13	4.8	109	95	78	0	282	255.29
F14	2.4	17	11	38	0	66	172.26
F15	11	66	66	61	0	193	217.25

Appendix C: Feeder Data

Table Appendix-C: The sample of Sabbata-I substation feeder-12 data

District	net_point_start	segment distance	Net_poin_end	Type_of_conductor	region_werda
WestAA	Degnet condominium	28	kara kore	AAAC_B_95mm ²	WEREDA 24
westAA	Kara kore	73	Kara kore	AAAC_B_50mm ²	WEREDA 24
WestAA	Welete silase mewcha	25	Welet mismar fabrica	AAAC_B_95mm ²	Alem Gena
westAA	Degnet condominium	31	Degnet condominium	AAAC_B_95mm2	WEREDA 24
westAA	Welete silase mewcha	16	Welet silase mewcha	AAAC_B_50mm2	Alem Gena
AA	Welete kobel	90	Welete kulkual sefer	AAAC_B_50mm2	Alem Gena
AA	Welete kobel	71	Welete kulkual sefer	AAAC_B_50mm2	Alem Gena
AA	Welete silase mewcha	288	Welet silase mewcha	AAAC_B_50mm2	Alem Gena
AA	Welete silase mewcha	15	Welete silase mewcha	AAAC_B_50mm2	Alem Gena
AA	Welete sefere	388	Wecheche	AAAC_B_50mm2	Alem Gena
AA	Degnet condominium	71	581226	AAAC_B_95mm2	WEREDA 24
AA	Welete sefera	91	Welete sefera	AAAC_B_50mm2	Alem Gena
AA	Welete silase mewcha	139	Welete silase mewcha	AAAC_B_50mm2	Alem Gena
AA	Welete kobel	515	Welete kulkual sefer	AAAC_B_50mm2	Alem Gena
AA	Welete sefera sefer	219	Welete sefera sefer	AAAC_B_50mm2	Alem Gena
AA	Welete	54	Welete	AAAC_B_35mm2	WEREDA 24
AA	Repi	35	Repi	AAAC_B_35mm2	WEREDA 24
AA	Welete	81	Welete	AAAC_B_35mm2	Alem Gena
AA	Walate Gosh Hotel	128	Walate condominium	AAAC_B_50mm2	WEREDA 24
AA	Repi	33	Repi	AAAC_B_35mm2	WEREDA 24
AA	Welete sefera sefer	81	Welete nemi	AAAC_B_35mm2	Alem Gena
AA	Korke	502	Korke	AAAC_B_50mm2	Alem Gena
AA	Welete	55	Welete	AAAC_B_35mm2	Alem Gena
AA	Repi	44	Repi	AAAC_B_50mm2	WEREDA 24
AA	Welete silase mewcha	108	Welete silase mewcha	AAAC_B_50mm2	Alem Gena
AA	Korke	204	Korke	AAAC_B_50mm2	Alem Gena
AA	Walate condominium	51	Walate condominium	AAAC_B_50mm2	WEREDA 24
AA	Kara	30	Kara	AAAC_B_35mm2	WEREDA 24
AA	Welete Mariam mewucha	335	Welete Mariam mewucha	AAAC_B_50mm2	Alem Gena
AA	Welete silase mewcha	55	Welete silase mewcha	AAAC_B_95mm ²	Alem Gena
AA	Korke	231	Korke	AAAC_B_50mm2	Alem Gena
AA	Welete kobel	216	Welete kulkual sefer	AAAC_B_50mm2	Alem Gena
AA	Welete	58	Welete	AAAC_B_35mm2	WEREDA 24
AA	Korke	55	Korke	AAAC_B_50mm2	Alem Gena
AA	Welete	520	Welete sefere sefer	AAAC_B_50mm2	Alem Gena
AA	Wele Mariam mewucha	90	W Mariam mewucha	AAAC_B_95mm2	Alem Gena
AA	Repi	77	Repi	AAAC_B_35mm ²	WEREDA 24
AA	Kara kore	9	Walate	AAAC_B_50mm2	WEREDA 24
AA	Welet Maryam mewcha	45	Welete	AAAC_B_50mm ²	Alem Gena
AA	Welete silase mewcha	4	Welet silase mewcha	AAAC_B_50mm2	Alem Gena