Investigation and Voltage Profile Improvement using D-STATCOM FACTS Devices

(A Case Study Welenchiti City Distribution System)

Tsehay Asrat Kidane

A Thesis Submitted to the

Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for Degree of

Master's in Electrical Power and Control Engineering

(Power System Engineering)

Office of Graduate Studies
Adama Science and Technology University

July, 2023

Adama, Ethiopia

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DECLARATION

I declare that this thesis entitled **"Investigation and voltage profile improvement using D-STATCOM FACTS devices (A Case Study of Welenchiticity distribution system)"** is my own work and has not been submitted to any university for similar purpose. The references used in this thesis are duly recognized by proper citations**.**

Tsehay Asrat Kidane__ ________________ ________________

Name of Student Signature Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled **"Investigation and voltage profile improvement using D-STATCOM FACTS device (A Case Study of Welenchiti city distribution system)"** prepared under my guidance by Tsehay Asrat Kidane submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power and Control Engineering (Power System Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Milkias Birhanu	_____________	________________
Major Advisor	Signature	Date

APPROVAL PAGE OF M.Sc. THESIS

I the advisor of thesis entitled **“Investigation and voltage profile improvement using D-STATCOM FACTS devices (A Case Study of Welenchiticity distribution system)”** and developed by Tsehay Asrat Kidane, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Milkias Birhanu	____________	__________________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Tsehay Asrat Kidane have read and evaluated the thesis entitled **“Investigation and voltage profile improvement using D-STATCOM FACTS devices (A Case Study of Welenchiti city distribution system)”** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering (Power Engineering).

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

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ACKNOWLEDGEMENTS

Primarily, I would like to give glory to God and the Virgin Mary without which the completion of this final thesis would have been unthinkable. I would like to extend deep appreciation to my Advisors, Dr. Milkias Birhanu, for their valuable suggestions, support, and constructive mentoring of my research effort. Furthermore, they dedicated their time to advising me throughout the entire assignment and suggested helpful comments to strengthen the thesis.

My sincere appreciations and acknowledgement continue to the data delivery organizations, Ethiopian Electric Utility and Ethiopian Electric Power staff members, Adama substation members and my entire department staff deserves special gratitude for their courteous cooperation in providing the required information for my thesis work.

Finally, I would like thank my beloved Husband Mr. Wendu Dereje and friends who always my side and encouraging and helping me in taking of my burden.

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ACRONYMS

AC	Alternate current
AVR	Automatic Voltage Regulator
AAC	All Aluminum Conductors
BIBC	Bus Injection to Branch Current
BCBV	Branch Current to Bus Voltage
DG	Distributed Generation
DLF	Direct Load Flow
D-STATCOM	Distribution Static synchronous compensator
DC	Direct current
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
FACTS	Flexible AC Transmission System
FBS	Forward/Backward Sweep
GTO	Get turns off
IGBT	Insulated-gate bipolar transistor
IEC	International Electro technical Commission
IEEE	International of Electrical and Electronics Engineers
KVAR	Kilovolt Ampere Reactive
KVA	Kilovolt Ampere
KCL	Kirchhoff’s Current Law
KVL	Kirchhoff’s Voltage Law
KV	Kilovolt
LV	Low voltage
MW	Mega watt
MVA	Mega volt Ampere
MATLAB	Matrix Laboratory(software)
PU	Per unit
PWM	Pulse with modulation
PSO	Particle Swarm Optimization

RDS	Radial Distribution System
SVC	Static var Compensator
SSSC	Static Synchronous Series compensator
STATCOM	Static Synchronous Compensators
TCSC	Thyristor Controlled Series Compensator
TSC-TCR	Thyristor Switched Capacitor Thyristor Controlled Reactor
THD	Total Harmonic Distortion
UPFC	Unified Power Flow Controller
UPQC	Unified power quality control
VSC	Voltage Source Converter
VSI	Voltage Stability Index

ABSTRACT

Ethiopia's electricity demand, like the rest of the world, is growing at an alarming rate, with electricity demand out stripping supply. One of the challenges is a reliable power supply with affordable energy prices and reduced CO2 emissions. Distribution feeders play a crucial role in transferring power from distribution substations to transformers near the customers' locations. However, certain issues such as low power factor, excessive loads, and long travel distances hinder their effectiveness in delivering electricity to connected customers. Voltage variations and under voltage are common problem for the Welenchiti city water pumping station, industries, commerce and residential end use. It is necessary to create techniques to improve the performance of distribution feeder voltage profile. To address these issues and improve the voltage profile of distribution feeders, integrating a D-STATCOM (Distributed Static Synchronous Compensator) into the R_7.2 Welenchiti distribution feeder can be a viable solution. Adama distribution substation, part of the Oromiya electric utility, has multiple outgoing feeders supplying power to Adama, Welenchiti, and koka towns. Among these feeders, the R_7.2 feeder has been chosen as the test system due to its long route and heavy loads. This work compares voltage profile and line losses (reactive power, active power) without any compensating device and then with compensating device (D-STATCOM). Forward/backward sweep load flow analysis and the PSO optimization technique were used to determine the best location and size of the compensation devices. Based on PSO the optimal size of a D-STATCOM is 999.8232 kVAr. Following this, simulation results shows that the active power loss is reduced from 2511.1KW to 229.0662KW and the reactive power loss is reduced from 1374.5KVar to 126.5238KVar. The reduction of the active and reactive power losses is 90.88% and 90.79% respectively and the minimum voltage becomes 0.96266p.u which confirms lower IEEE voltage limit.

***Keywords**: D-STATCOM, PSO,* MATLAB, *Voltage profile improvement, Backward/Forward Sweep*

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CHAPTER ONE

1. INTRODUCTION

1.1 Background

One of the most crucial components of a power system utilized to supply electrical energy to end users is the electric power distribution system. Between the primary substation and the neighborhood end user's meter terminal is where it is situated. Using step down transformers, also known as step down transformers, it steps down the generated electrical power from the transmission network to a lower voltage magnitude, which typically varies from 2.4 KV to 33KV.Basic elements of distribution systems include distribution substation, feeders, distributors, transformers and service mains. In accordance with the classification criteria, there is different type of distribution system. A distribution system can either a DC distribution system or an AC distribution system based on its nature, while there are overhead and underground type of distribution system based on their contraction.(Yuan, H. Minyou and C., 1994).

Power distribution systems should, in theory, deliver energy to users continuously in sufficient and secure manner. However, in reality, power system, particularly distribution system, have a number of issues that have a substantial negative impact on consumers' comfort & economics in every sector during various operation times. A power loss is the discrepancy between the energy provide to the distribution system and the energy bills sent to customers. Power losses always occur when delivering power from source to client point. Technical and non-technical losses are the two main categories into which the causes of power losses in distribution network are typically separated. Technical losses include electric losses resulting from conductors carrying current, magnetic losses in transformers, resistive losses in windings and cores, resistive losses in service lines, and losses in KWH meters. Technical losses relate to the physical characteristics of the conductor and equipment. Although these losses cannot be completely avoided, they can be minimized with sufficient care. Power theft by hooking the lines, unauthorized connections from power lines, loss at the loose connection ends, improper power meter reading, incorrect invoicing, unlisted meters, trees in contact with overhead power lines, etc. are examples of non-technical losses. There are many approaches to cut losses, including network reconfiguration, capacitor placement, VAR compensation, smart metering installation for non-technical losses, and distributed generation. (Subiyanto, 2018).

The violation occurred due to fluctuations in voltage (both under- and over-voltage), changes in frequency, voltage imbalances caused by faults in transmission and distribution lines, and excessive total harmonic distortion (THD) in currents. Despite the existence of these issues, there are no universally accepted standards specifying the minimum reliability requirements for electric power. Among these problems, voltage variations and interruptions are particularly detrimental to the industry. Another issue in distribution networks is voltage drop, which arises when distribution feeders transport power over long distances or serve large loads. Depending on the load current, distribution feeders either consume or supply reactive power. When the load is below the surge impedance loading, feeders generate a net reactive power, while at loads above the surge impedance load, they absorb reactive power. This voltage drop problem can occur as a result of these factors.

The Adama distribution substation is part of the Oromiya Electric Utility's network and serves various areas, including Adama, Welenchiti, and Koka town. It comprises 11 outgoing feeders that distribute power to different regions. Furthermore, the Adama 132kV substation receives power from the 132kV Koka substation and Adama wind generation via a single 132 transmission line. The low voltage feeders in the Adama substation face challenges such as overloaded lines, frequent power interruptions, and low voltage at customer premises. These significant reliability issues in the power distribution system create difficulties for consumers and adversely affect service quality, particularly in the provision of drinking water in Welenchiti city.

Installation of highly advanced equipment is required to improve voltage profile and stability while increasing system performance; these devices include capacitor banks, shunt and series reactors, automatic voltage regulators (AVR), and recently developed Distribution Network Flexible AC Transmission (FACTS) devices like the Static Synchronous Series Compensator (SSSC), Distribution Static Compensator (D-STATCOM), and Unified Power Quality Controller. (T. Yuvaraj, K. R. Devabalaji, and K. Ravi, 2015)

This has increased the motivation to choose distributed D-STATCOMs as means of compensation for loss reduction and voltage improvement.

1.2 Case Study Area Description

The research site is in the northern part of the Main Ethiopian Rift, in the east shoa zone of Oromiya National State, 130 kilometers from Addis Ababa.

Zone: East Shewa
Woreda: Boset
Region: Oromiya
Location: 08°39′48″N 39°26′4″E
Elevation: 1,460 m (4790 feet)

Figure 1.1 Location of the site (Welenchiti city) [Google map]

1.3 Statement of the Problem

The percentage of people living in cities is rising steadily and gradually. The demand for electrical energy from residential users, business customers, and industrial enterprises also rises as a result. The distribution networks face significant challenges such as high R/X ratio, severe voltage drop, and feeder failures, resulting in considerable power losses. These reliability issues complicate consumer activities and reduce service quality. These severe dependability issues with the power distribution system complicate consumer activities and low service quality. Overloading their carrying capacity, the distribution feeders that deliver electricity from the substation to the customers are currently in use. Long-distance distribution feeders that are overloaded have significant losses and voltage drop issues. Voltage variations and under voltage are common problems for the Welenchiti city water pumping station, industries, commerce, and residential end use. Due to this reason, finding enhancement techniques to the voltage profile, a scientific solution is highly required. Therefore, it is crucial to find techniques to enhance the voltage profile and find scientific solutions to these problems. To address these challenges, D-STATCOM has superior features when compared to other reactive power compensation devices, including low power losses, minimal harmonic output, high regulating capabilities, low cost, and compact size and also Particle Swarm Optimization has the advantage of parallel computation and robustness, and it can find the global optimal solution with a higher probability and efficiency than traditional methods. It is also easy to realize, fast converging, intelligent and capable of determining near global solution with lesser computational burden. This thesis focuses on improving the voltage profile of the Welenchiti distribution system through the optimal allocation of D-STATCOM using the Particle Swarm Optimization algorithm and MATLAB-Simulink software.

1.4 Objectives

1.4.1 General Objective

The main objective of this thesis is to investigation and Voltage Profile Improvement by using D-STATCOM as FACTS Devices in Power Distribution System.

1.4.2 Specific Objectives

To achieve the main goals, the study has the following specific objective:

- To assess the voltage profile of an existing distribution network.
- To analyze all the relevant data from the substation feeders.
- To Select size and location of D-STATCOM using PSO for the Welenchiti distribution network feeder.
- To model and simulate the entire distribution system along with the PSO algorithm within the MATLAB software.

1.5 Scope and Limitation of the Study

This study focuses on voltage problem-minimizing solutions for the distribution feeder by optimal placing and sizing of D-STATCOM using particle swarm optimization. The goals of this work is to simulate the proposed system using MATLAB simulation tools and to examine how the system's performance changes before and after modification.

1.6 Significance of the Study

The output of this thesis work is very significant to both customers and the Ethiopian Electric Utility (EEU). Some of the benefits are:

- The voltage profile of its electrical power supply has increased.
- Reliability of its electric power system is increased.
- To show D-STATCOM is the best-compensating device for improving distribution system performance.
- Improves the product quality of industries and increases customer satisfaction.

CHAPTER TWO

2. LITERATUREREVIEW

2.1 Electrical power distribution systems

The distribution system, which connects the high voltage transmission network to the low voltage consumer service point, is a component of the electrical power system. Any distribution system uses feeders, distributors, and service mains to distribute power. Feeders are huge current-carrying cables that deliver current in big quantities to feeder sites. Distributors are conductors that allow current to be drawn from a supply and directed to a consumer's location. A service main typically consists of a short cable that links the terminals of the distributor to the consumer.

Electric power distribution refers to the process of delivering electricity from the transmission system to individual consumers, businesses, and other power-dependent infrastructure. The primary means of transporting medium voltage electricity to the customer's location is through primary distribution lines, which lead to distribution transformers. The primary distribution system of the electric distribution system serves as the connection between the distribution substation and distribution transformers. The system is composed of secondary feeders or distribution feeders, which are circuits responsible for delivering power. A standard power distribution feeder supplies power to both the primary and secondary circuits.

An electrical grid refers to a system of interconnected power lines that facilitate the transportation of electricity from power generation facilities to end consumers. This network comprises power-generating stations responsible for electricity production, high-voltage transmission lines that transmit power over long distances from remote sources to areas of demand, and distribution lines that connect with end consumers. Within substations, high voltage power lines pass through step-down transformers, which convert the electricity into a usable voltage level. This voltage is then divided and distributed in different directions through low voltage power feeders.(Desta, 2019)

2.2 Power Loss and Voltage Drop

Several factors, including power losses in transmission and distribution lines, transformers, capacitors, and insulators, among others, contribute to the overall electrical power losses in distribution systems. These losses can be classified into two types: actual power losses and reactive power losses. Actual power losses occur due to line resistance, while reactive power losses are caused by reactive elements in the system. While utilities primarily focus on minimizing actual power losses as they affect energy delivery efficiency, reactive power losses are also significant. This is because maintaining the appropriate voltage level in the system requires controlling the flow of reactive power at a specific level, which enables the flow of actual power. The distribution network, which connects to end consumers, completes the power system. Faults in the distribution network impact both consumers and utilities. One of these issues is voltage drop, which must be minimized to ensure that voltages at load locations remain within acceptable limits. Voltage drop problems often arise when using long-distance lateral radial feeders or when supplying power to large loads. Therefore, it is crucial to find a solution to address this problem and maintain control over the voltage at various nodes in the system. In practice, "voltage control" refers to the regulation of reactive power, as controlling reactive power and regulating node voltages help reduce power losses, a significant concern for utilities. Distribution systems are equipped with various voltage regulating devices such as network restructuring, implementation of Distributed Generation (DG), tap change transformers, voltage regulators, shunt/series capacitors, and integration of Flexible AC Transmission System (FACTS) devices to enhance voltage and control reactive power.(L.Ramesh, .P.Chowdhury and S.Chowdhury, 2009)

2.3 Factors Affecting Voltage Drop and Power Loss in Distribution System

A number of factors contribute to the distribution network's rising voltage fluctuation and distribution feeder loss. Line impedance and current passing through the conductor are the two primary factors that determine of a line's voltage drop. The voltage drop will consequently rise with an increase in impedance or current. Some of the known factors that affect distribution line losses directly or indirectly and voltage drop are given below. An electric supplier that intends to minimize line losses must first take these considerations into perspective.

- **Conductor poor joints and terminations:** A significant reason for significant voltage drops in the feeder is attributed to inadequate joints and terminations. Poor joints and terminations occur when there is a loose connection between two interconnected conductors. This loose contact creates a strong resistance to the current flow, generating heat in the process. Consequently, the resistance increases, resulting in a voltage drop at that particular location.(Reza Indra Satrio and Subiyanto, 2018)
- **Joint hot spots:** Joint hot spots arise when there is a creation of mechanically weak joints or terminations, resulting in high resistance points. This high resistance causes localized heating, which in turn promotes oxidation and creep. Consequently, the connection becomes looser, leading to additional heating until the contacts begin to glow. At this stage, a greater voltage loss is observed as the thermal resistance of aluminum and copper increases.
- **Using Under-Sized Conductors:** When compared to the electrical resistance of a conductor, which is a measurement of how challenging it is to push the charges along, voltage can be thought of as the force pushing charges along a conductor. Electrical resistance, when compared to flow, is similar to friction for currents that are flowing; long thin cables offer greater resistance than short thick wires.
- **Using Non-Uniform Conductor Material:** Corrosion is an important factor to consider when selecting conductor materials. The two types of corrosion that have the greatest impact on a metal's electrical properties are oxidation and galvanic corrosion. When selecting conductor metals, consider galvanic corrosion, which is caused by an electrical potential difference between two or more metals.
- **Loads on the main feeder:** The currents in each feeder segment along its distribution feeder are determined by the loads connected to the feeder's downstream section. The voltage variation is affected by the current even though the feeder impedance is unaffected.
- **Low voltage level:** Due to the majority of residence and commercial loads being inductive, even small fluctuations in voltage can have an impact on the efficiency of the equipment and raise system losses. Low voltage levels affect the lifespan of electric products as well.(singh, 2018)

- **Lengthy distribution lines:** A feeder's series impedance is linearly inversely proportional to its length. As a result, voltage fluctuation is significantly influenced by the length of the feeder.
- **Location of Distribution transformer:** The system suffers energy losses as a result of the distribution transformer's improper placement; for instance, the farthest consumers receive much lower voltage than those who are close to the transformer.
- **Unbalanced phases:** It is impossible to distribute the load equally throughout all the phases since the load locations are dispersed at random. Power losses result from the current flowing in the neutral during this unbalanced phase.
- **Poor quality of equipment's:** As a result of not meeting electrical standards and drawing a lot of current, low-quality equipment results in substantial losses. Heat and I^2R losses were induced by high current.
- **Low Power factor:** The power factor is the ratio of actual power to apparent power. When two power factor systems produce the same amount of real power, the system with the lower power factor will have a higher reactive power current, resulting in a higher voltage drop and higher loss.

2.4 Distribution Network Power loss and Voltage drop Minimization Techniques

There are several methods available to mitigate power loss and voltage fluctuation in a distribution feeder. These techniques include network reconfiguration, conductor grading (network re-conducting), optimal positioning and sizing of distribution transformers, reactive power compensation, employing highly efficient transformers, implementing high voltage distribution systems, incorporating distributed generation, and constructing new substations. The following section covers the approaches used to minimize voltage drop and power loss.(singh, 2018)

Network reconfiguration: It involves manipulating switches to modify the circuit topology in order to achieve cost reduction while adhering to specified constraints. Various constraints are taken into consideration, such as upper and lower limits for bus voltage and line current. Network reconfiguration serves as a technique for minimizing losses in a distribution system. This approach involves altering the power flow by introducing additional feeder links to create a tree structure or by opening or closing vital switches within the feeder.(Ayodeji Olalekan salau,Yalew Werkie Gebru and Dessalegn Bitew, 2020)

Power distribution network reconfiguration enables the transfer of loads from heavily loaded feeders to lighter-loaded feeders and from higher resistance routes to lower resistance routes to achieve the lowest loss, where the resistance route is the overall resistance from the source to the load point. Such transfers not only succeed in adjusting the loads on the switched feeder and reducing losses, but they are also effective in enhancing the voltage profile along the feeder and overall system power losses.(Chidanandappa. R, Dr.T.Ananthapadmanabha & Ranjith. H.C, 2015)

Conductor grading: Conductor grading is a method used to decrease resistance in a feeder by replacing the existing conductor with a new conductor of the appropriate size for the desired feeder length, considering cost-effectiveness. This can be achieved by installing auxiliary conductors to operate in parallel with the existing ones or by replacing smaller-sized conductors with larger ones having a greater cross-sectional area, thereby reducing the corresponding resistance. However, the cost of the conductors and their installation often exceeds the energy savings achieved. As a result, these approaches, despite their potential for significant loss reduction, are not commonly employed unless there is a specific need. Conductor grading is typically implemented when the performance of a conductor is compromised due to rapid load growth. The selection of conductors in this technique aims to minimize power loss and voltage drop in the distribution system, making it suitable for developing nations experiencing significant annual population growth (and energy demand).(Taye, 2019)

Locating and Sizing Distribution Transformers: If distribution transformers are not strategically located close to the consumers, even though the voltage level may remain satisfactory at the transformer's secondary, customers situated farther away will receive significantly reduced power. Consequently, the distribution system experiences higher losses. To maintain an optimal voltage level, it is essential to position distribution transformers as close as possible to the load center. Furthermore, larger transformers should be replaced with smaller ones that can effectively serve a smaller number of users.

Using a High-Voltage Distribution System: Voltage fluctuation and distribution system loss could be decreased by using a high voltage distribution system. High-voltage cables are moved as close to the load as is feasible, and a variety of small-rated transformers are used to replace huge ones. It is also possible to upgrade existing low voltage distribution systems to high voltage distribution systems. This technique is more efficient and reliable for reducing technical losses and improving power quality in distribution networks. Since the current in a high-voltage devices is quite low. But it could not be possible considering the size of the initial investment**.**

Reactive Power Compensation: The management of reactive power to enhance the effectiveness of the ac power system is known as reactive power compensation. Reactive power compensation concerns often involve load and voltage support. The objectives of load support are to reduce current harmonic components brought on by huge and erratic nonlinear industrial loads, increase voltage regulation, balance real power extracted from the ac supply, and improve system power factor. To lessen voltage swings at a transmission lines terminal, voltage support is typically required. Reactive power adjustment in transmission systems improves the stability of the ac system by enhancing the maximum active power that can be delivered.(Dixon, Juan W and Morán, Luis A, 2008)

In general, if the size and placement have been done optimally, reactive power compensation is an important way to enhance the voltage profile and loss of a distribution network.

2.5 Overview of FACTS

2.5.1 Introduction

The IEEE defines it as: "Power-electronic and other static controllers are employed in alternating current transmission systems to enhance controllability and increase the capacity for power transfer. Solid-state transmission technologies have emerged as a result of the demand for electrical systems that are more effective and quicker to react. These so-called FACTS devices improve stability and raise line loads so they are closer to thermal limitations.

2.5.2 Classification of FACTS Devices

One or more ac transmission system parameters can be controlled by a power electronic-based system and other stationary equipment. There are 4 different sorts of controllers, according to facts:

1) **Shunt Connected FACTS Controllers**

These FACTS devices serve to maintain the voltage profile while minimizing losses by strategically installing FACTS in the power system network. Shunt controllers are used to inject current into the line. Reactive power is provided when the injected current is in the quadrature phase with the line voltage; otherwise, actual power is used. Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are two examples of this sort of shunt controller.

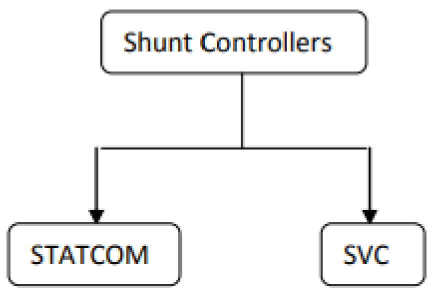

Figure 2.1 Type of shunt controllers (N.Verma, 2014)

I) Static Synchronous Compensator (STATCOM)

STATCOM: "IEEE Definition: A static synchronous generator used as a shunt-connected static VAR controller, allowing the control of the output current, either capacitive or inductive, without regard to the ac system voltage."

STATCOM is a control system for alternating current electricity transmission networks that is based on a voltage source converter in power electronics. It can supply or absorb reactive AC power to a network of electrical devices. It offers active AC power when connected to a power source. A member of the FACTS device family is STATCOM. STATCOM is placed in support of electrical networks that have poor voltage regulation and power factor. Voltage stability is the application that is used the most frequently. In terms of the dynamic stability of a power system, STATCOM offers better dampening than the SVC because it can exchange active power with the system immediately.

II) Static Var Compensator (SVC)

SVC: According to the IEEE, a static VAR generator or absorber with a shunt connection is one whose output is changed to exchange capacitive or inductive current in order to maintain or regulate particular electrical power system parameters. SVCs are first generation FACTS devices comprising of TCR and FC/TSC power electronics equipment to supply/absorb Reactive power to/from the system efficiently.

TCR is an inductor that is shunt-connected and Thyristor-controlled, and whose reactance is modified by the Thyristor valve's partial conduction control. The firing angle can be changed to change the system's reactive power. There are no harmonics produced in this "continuous control" process.

TSC is known for its "stepwise action by full or zero conduction control" and its ability to provide minimal losses, harmonics, redundancy, and flexibility. It consists of several shunt-connected inductors that a Thyristor switches in and out of without changing the firing angle, and is used to turn on and off shunt capacitor units.

2) Series Connected FACTS Controllers

The placement of FACTS devices strategically within the power system network is an effective approach for power flow control and reducing system losses. Series controllers are utilized to inject voltage in series with the transmission line. Depending on whether the injected voltage is in phase quadrature or not, it either provides reactive power or active power. These series controllers are particularly useful for long-distance transmission lines. By connecting a capacitor bank in series with the line, the reactance of the transmission line can be partially neutralized. Examples of series controllers within this device family include the static synchronous series compensator (SSSC), Thyristor-controlled series capacitor (TCSC), and Thyristor-switched series capacitor (TSSC).

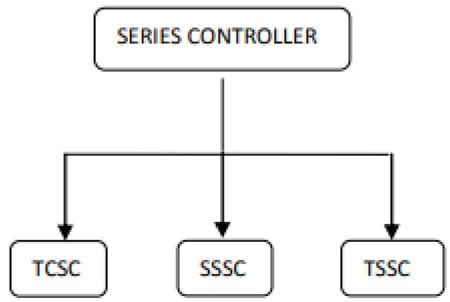

Figure 2.2 Types of series controller (N.Verma, 2014)

I) TCSC: A capacitive reactance controller, as defined by the IEEE, consists of a series capacitor bank that is shunted by a reactor controlled by a Thyristor. This arrangement allows for the continuous adjustment of the series capacitive reactance. The initial version of FACTS, known as Thyristor-controlled series capacitor (TCSC), involves the introduction of a Thyristor-controlled capacitor in series with the transmission line to modify the line impedance. The TCSC, functioning as a series-controlled capacitive reactance, enables the continuous control of power flow on the AC transmission line across a wide range. To understand the operation of TCSC, one can analyze the behavior of a variable inductor connected in series with a fixed capacitor.

II) SSSC: The static synchronous generator, as defined by the IEEE, is employed as a series regulator to manipulate the reactive voltage drop across a transmission line and control the transmitted electric power. It operates without the need for an external power source and produces a voltage that is orthogonal to the line current, providing independent controllability. The SSSG is connected in series with the transmission line via a transformer, and a voltage source converter (VSC) is used for SSSC. To ensure a constant voltage supply and compensate for VSC losses, an energy source is required. The utilization of SSSC enables the exchange of both active and reactive power. If the objective is to balance reactive power, a small energy source may suffice. However, if precise regulation of the injected voltage in terms of phase and magnitude is desired, a larger energy source is necessary. By compensating for reactive power, the voltage can be controlled since the voltage vector forms a 90° angle with the line current. SSSC can be continuously controlled at any value and during any operational period of the VSC.

III) TSSC: IEEE Definition: A Thyristor switched reactor switches the series capacitor bank within a capacitive reactance controller to offer progressive control of series capacitance reactance. (N.Verma, 2014)

3) Combined Series-Shunt Controllers

These controllers are a hybrid of shunt-type and series-type controllers. As a result, they exhibit the characteristics of both types of controllers and can be used to manage voltage profiles as well as power flow, thus minimizing losses and improving system reliability, flexibility, and security. Unified Power Flow Control, or UPFC, is an example of series-shunt controller.

UPFC: As a combination of SSSC and STATCOM, the series-shunt controller, such as UPFC, incorporates the characteristics of both controller types without relying on an external energy source. These controllers are capable of performing multiple tasks, allowing simultaneous or separate control of parameters such as bus voltage, transmission line reactance, and phase angle between two buses. UPFC is specifically designed for managing in-phase voltage, quadrature voltage, and shunt compensation, making it a highly adaptable and advanced power electronic device for regulating and optimizing power flow in electrical power transmission systems. It offers various potential benefits for both static and dynamic operations of transmission lines. Through real-time control and dynamic compensation, UPFC provides the necessary multifunctional flexibility to address numerous challenges in the power sector. By regulating key variables that impact power flow in transmission lines, UPFC effectively enhances both the actual and reactive power flow, contributing to improved stability of the power system when integrated with FACTS devices.

4) Combined Series-Series Controllers

In order to provide independent series reactive compensation for each line in multi-lane transmission lines, a combination of several series controllers is employed in a coordinated way. However, it can use a power link to transfer real power over lines. Alternately, the DC terminals of converters can be interconnected via unified controllers. This will assist in supplying the transmission line with real power.

The Interlink Power Flow Controller (IPFC) is an illustration of this kind of technology. (Singh Naveen, AgnihotriPiyush, 2018)

2.5.3 Advantage of FACTS Devices in Distribution Systems

They contribute to achieving the best system performance by minimizing power loss and enhancing voltage profile. The power carrying capacity of lines can be enhanced up to their thermal limit due to the quick controllability of FACTS controllers. The system's dynamic security is enhanced by raising the transient stability limit. The FACTS controller can be used to solve the dynamic over voltage issue. The controllability is utilized in the majority of applications to prevent expensive or physically demanding extensions of power systems, such as improvements or additions to substations and power lines. FACTS-devices improve the use of existing installations and offer a greater response to changing operational conditions.

2.6 Distribution static synchronous compensator

STATCOM is an AC voltage source converter device that effectively manages the active and reactive power requirements of the system by converting a DC input voltage into an AC output voltage. Compared to SVC (Static Var Compensator), STATCOM offers distinct advantages. Notably, when the system voltage drops to a level where the STATCOM output reaches its maximum capacity, the voltage magnitude no longer affects the maximum reactive power output. Additionally, when the voltage falls below the specified limit, STATCOM exhibits constant current characteristics. At the distribution level, these STATCOM devices are commonly referred to as D-STATCOMs (Distribution STATCOMs).(Fahad Iqubal, Mohd Tauseef Khan, Anwar Shahzad Siddiquii, 2017)

The Distribution Static Synchronous Compensator (D-STATCOM) is an electrical device that operates as a shunt component and utilizes force-commutated power electronics (such as GTO or IGBT) to control power flow and enhance transient stability in electrical power networks. It falls under the category of Flexible AC Transmission System (FACTS) devices. The D-STATCOM is a three-phase Voltage Source Converter (VSC) connected in parallel with the distribution network to regulate bus voltage, improve power factor, and manage reactive power. At the point of common coupling (PCC), this device has the capability to inject or absorb both active and reactive current. However, due to limitations associated with energy storage, the D-

STATCOM is unable to inject active power for extended periods of time. The exchange of power between the D-STATCOM and the system primarily occurs through reactive power, resulting in steady-state operation. A typical configuration of the D-STATCOM for steady-state operation consists of a coupling transformer with leakage reactance, GTO/IGBT, voltage source converter (VSC), and a DC capacitor.(F. Iqbal, M. T. Khan, and A. S. Siddiqui, 2018). Figure 2.3 below shows a basic construction of DSTATCOM to the 3-phase distribution line.

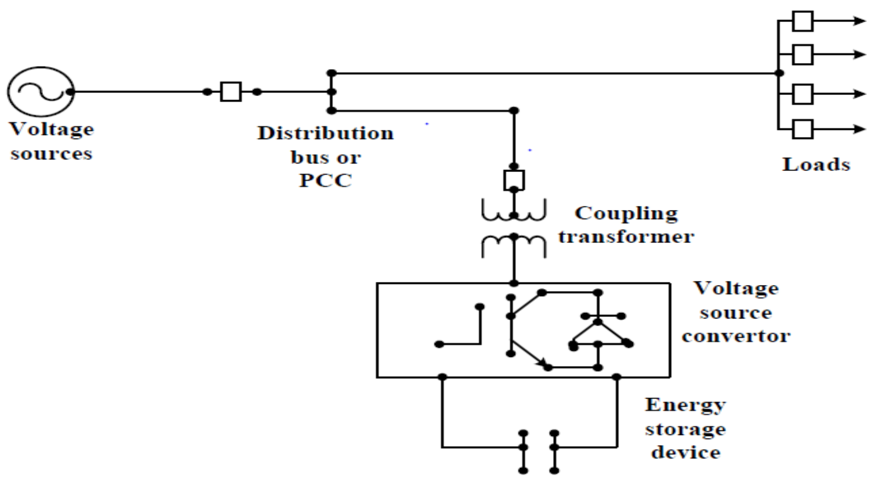

Figure 2.3 Basic Structure of D-STATCOM (Piyushkumar M. Saradva, Mahesh H. Pandya, 2016).

2.6.1 Basic Operating Principle of D-STATCOM

A D-STATCOM is a solid-state power electronic switching device that consists of a controller, a coupling transformer, an energy storage device, and a VSC. Depending on the needed compensation, D-STATCOM has the ability to generate and absorb reactive power. The power networks at a PCC, where the voltage-quality issue appears are connected to the D-STATCOM. The controller computes the necessary voltages and currents and compares them to the commands. In order to drive the power converter, the controller generates a set of switching pulses and then applies feedback control.

The output voltages' amplitudes are changed to exchange reactive power with the network. The system voltage Vs and the Vsc's output voltage are adjusted in phase. The following provides an explanation of how reactive power exchange occurs between output voltage and AC system voltage.

- The D-STATCOM will function as a capacitor and provide reactive power (capacitive mode) if Vvsc is greater than Vs.
- The D-STATCOM will function as an inductor and use reactive power (inductive mode) if Vs is greater than Vvsc.
- The reactive power is zero (No-load mode) if Vvsc equals Vs and D-STATCOM neither generates nor absorbs reactive power.

The three operating modes of DSTATCOMS are shown in Figure 3.4 below:

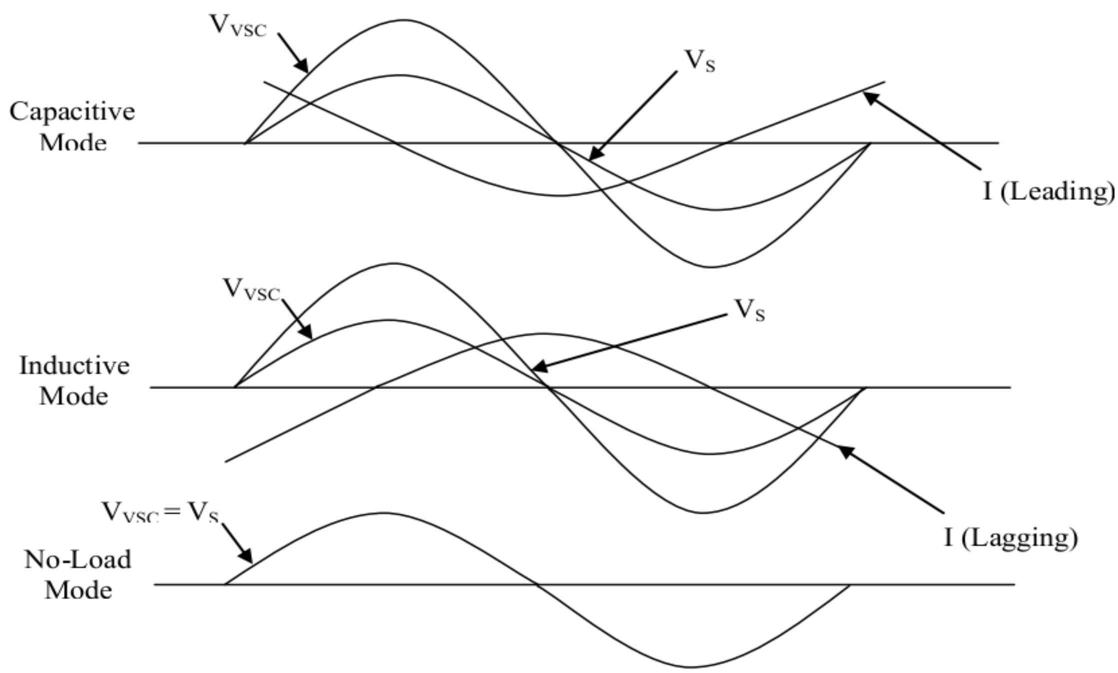

Figure 2.4Operating Modes of D-STATCOM (Asare, 1994)

2.6.2 Components of D-STATCOM

D-STATCOM consists of several components, including a three-phase inverter that commonly utilizes PWM (Pulse Width Modulation) technology with SCRs (Silicon-Controlled Rectifiers), MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors), or IGBTs (Insulated-Gate Bipolar Transistors). The inverter is powered by a DC capacitor that supplies it with a stable DC voltage. To eliminate high-frequency components caused by the PWM inverter, a link reactor is employed, connecting the inverter output to the AC supply side filter components. The inverter converts the DC voltage from the capacitor into a three-phase voltage, which is synchronized with the AC supply. The link inductor connects the system voltage to the AC supply side, ensuring their proper integration.

2.6.3 Reasons for choosing D-STATCOM

Ensuring that the power demand is met while maintaining voltage levels within an acceptable range is a crucial requirement in distribution systems. To regulate voltage, two commonly used methods are series voltage regulators and shunt capacitors. However, both of these methods have some drawbacks, Traditional series voltage regulators lack the ability to generate reactive power and have slow response times due to their step-by-step operations. Shunt capacitors, on the other hand, cannot provide continuously variable reactive power and may cause oscillations when used in circuits with inductive components. In comparison, D-STATCOM, a shunt FACTS (Flexible AC Transmission Systems) device, is preferred as a compensating device. It offers independent voltage regulation, faster power factor correction, continuous and variable output without abrupt steps, harmonics, or transients. D-STATCOM can generate and absorb reactive power, operate near system stability limits, and respond almost instantaneously. The reaction begins about <10 milliseconds after the incident, reaches full power in 20 to 50 milliseconds, and remains in "hot standby" throughout, with power losses of about 1%. The annual cost savings, power losses, load ability, stability, and quality of the electricity are all increased with the placement of DSTATCOMs.(Wasiak, Irena, RozmyslawMienski, RyszardPawelek, and Piotr Gburczyk, 2007)

2.7 Particle swarm optimization

PSO has been identified as the most effective heuristic optimization technique for systems consisting of nonlinear programming problems that involve multiple iterations. Due to its ability to adapt to the responses of the multi-iteration nonlinear power flow algorithm, PSO is considered a promising approach for achieving improved outcomes in terms of the placement and sizing of Flexible AC Transmission Systems (FACTS) devices. Introduced by James Kennedy and Russell Eberhart in 1995, PSO is a population-based optimization technique specifically designed for continuous nonlinear functions, making it a valuable tool in this context.(Sanyal, 2021)

PSO starts with a set of particles, representing potential solutions, randomly distributed in a search space. Each particle has its own fitness value, reflecting its suitability as a solution to the problem at hand. The goal is to improve the fitness of each particle over iterations. The velocity of each particle is adjusted in every iteration, dictating its movement within the search space. Through interactions with the best solutions encountered by the group and its own best position, particles gradually converge towards optimal solutions. The velocity update takes into account the particle's prior velocity, its best position, and the best position of the entire swarm. PSO is particularly effective in solving optimization problems, especially those that are non-linear, non-convex, and involve continuous or discrete variables.(Mandefro, 2020)

2.7.1 Advantage and Disadvantages of PSO Technique

Advantages of PSO algorithm

- Application to both scientific research and engineering use.
- PSO have no overlapping and mutation calculation.
- The speed of particle transmission is very fast.
- PSO adopts the real number code which is directly described by the solution.
- It has global search efficiency and a derivative-free algorithm.
- Calculation in PSO is very simple.
- The search in PSO can be carried out by speed of the particle.

Disadvantages of PSO algorithm

- PSO method suffers from partial optimization.
- The partial optimism of the PSO algorithm weakens the regulation of its speed and direction.
- PSO method cannot also solve the problem of non-coordinate systems.
- PSO method cannot solve the problem of scattering

2.8 Load Flow Analysis for Radial Distribution System

In order to calculate the voltages at each node and the currents at each branch, load flow analysis is a critical task in the regulation of power systems. Many analyses would not be possible without the results of the load flow method because they contain essential data about the power system. Applications of load Flow techniques decrease the requirement for extra power system investments in communication and sensor infrastructure. Several tools that track, analyze, and manage the power system also include load flow results. Numerous power system applications, including distributed generator and capacitor placements, economical dispatch, power quality enhancements, network reconfiguration and service restorations, power systems optimization, among others, use load flow analysis directly or indirectly. Power flow analysis in both distribution and transmission a network has been developed using a variety of load flow techniques. In distribution networks, backward/forward sweep (BFS) and direct load flow (DLF) methods are frequently used to analyze power flow. In power transmission systems, the Newton Raphson, Gauss Seidel, and fast-decoupled methods are typically used.

Due to the high resistance (R) to reactance (X) ratio in distribution networks, the load flow techniques utilized in a power transmission network might not function effectively there. The Newton-Raphson approach for distribution networks applications has been improved by a small number of researchers, but it still takes a long time to compute. This paper makes use of the backward/forward sweep (BFS) power Flow analysis using Kirchhoff's rules, which is more appropriate for distribution systems. (al, 2021)

2.8.1 Forward / Backward Sweep Load Flow Method

There is a distinct route from each bus back to the source in the radial distribution network, which makes it special. The forwarding and/or backward sweep processes that make use of the radial network structure make up the backward/forward sweep algorithm. It is based on updating voltages and currents along these distinct routes. To determine the node voltages, the forward sweep begins at the sending end and moves to the far end of feeds. As a result of currents or power flows injected into each lateral, calculate the voltage drop to update end voltages. It is based on the source voltage's defined boundary condition. It mostly involves calculating voltage drops, with potential updates for current or power flows. On the other hand, backward sweeping of the feeder and laterals from the far end to the sending end can be used to obtain the branch current or power. It is based on the boundary condition of no current or power flowing out of the lateral end. In order to perform the load flow, two derived matrices known as the bus-injection to the branch-current matrix (BIBC) and the branch current to the bus-voltage matrix (BCBV) are produced by applying Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) to backward and forward propagations, respectively. (J. A. Michline Rupa and S. Ganesh, 2014)

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

Branch currents from loads to origin are collected for each iteration k. However, in order to determine the branch current, we must first determine the current injected at each bus as well as the bus-injection to branch current (BIBC) that connects the bus injected current to the branch current. The current injection at the k^{th} iteration of the i^{th} bus is

$$I_i^k = \left(\frac{s_i}{v_i^k}\right) = \left(\frac{P_i + jQ_i}{v_i^k}\right) \quad 2.1$$

$$S_i = P_i + jQ_i \quad 2.2$$

Where: -

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

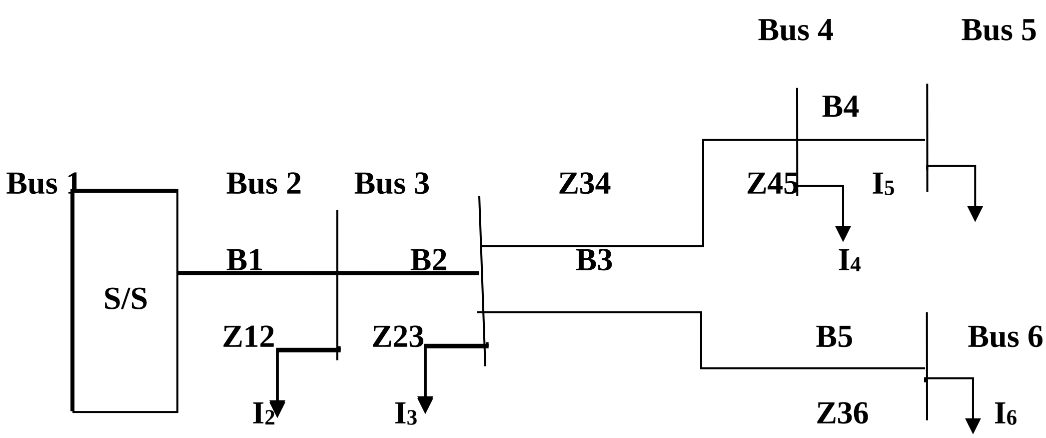

Figure 2.5Simple 6-bus distribution system

The branches current is now determined using Kirchhoff's current law (KCL) on the sample shown in figure 2.5. When defined in terms of equivalent current injections (Ii), the branch currents (Bi) can be written as

$$
\begin{aligned}
B_1 &= I_2 + I_3 + I_4 + I_5 + I_6 \\
B_2 &= I_3 + I_4 + I_5 + I_6 \\
B_3 &= I_4 + I_5 \\
B_4 &= I_5 \\
B_5 &= I_6
\end{aligned}
\qquad 2.3
$$

As a result, the relationship between the branch currents and the bus current injections can be described in a matrix, as shown below:

$$
\begin{bmatrix} B1 \\ B2 \\ B3 \\ B4 \\ B5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I2 \\ I3 \\ I4 \\ I5 \\ I6 \end{bmatrix} \qquad 2.4
$$

Equation (2.4) can be expressed as

$$[B] = [BIBC][I] \qquad 2.5$$

Where: -

BIBC is the bus injection branch current for the given sample network

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

Using the branch current vector B and branch-current to bus-voltage (BCBV) values that were previously determined, Kirchhoff Voltage Laws (KVL) are now being applied.The following equations can be used to connect bus voltage and branch current.

$$V_2 = V_1 - B_1 Z_{12} \qquad 2.6$$

$$V_3 = V_2 - B_2 Z_{23} \qquad 2.7$$

$$V_4 = V_3 - B_3 Z_{34} \qquad 2.8$$

$$V_5 = V_4 - B_4 Z_{45} \qquad 2.9$$

$$V_6 = V_5 - B_5 Z_{36} \qquad 2.10$$

Where: -

V_i is the voltage of bus i

Z_{ij} is the line impedance between bus i and bus j

The bus voltage can be expressed as a function of the substation voltage, line parameters, and branch currents. The above bus voltage calculations can be changed and rearranged to become

$$V_2 = V_1 - B_1 Z_{12} \quad 2.11$$

$$V_3 = V_1 - B_1 Z_{12} - B_2 Z_{23} \quad 2.12$$

$$V_4 = V_1 - B_1 Z_{12} - B_2 Z_{23} - B_3 Z_{34} \quad 2.13$$

$$V_5 = V_1 - B_1 Z_{12} - B_2 Z_{23} - B_3 Z_{34} - B_4 Z_{45} \quad 2.14$$

$$V_6 = V_1 - B_1 Z_{12} - B_2 Z_{23} - B_3 Z_{34} - B_{4_5} Z_{45} - B_5 Z_{36} \quad 2.15$$

The above bus voltage calculations can be changed and rearranged to become

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \quad 2.16$$

$$[\Delta V] = [BCBV][B] \quad 2.17$$

In general form, with i and k denoting the node and iteration number respectively

$$I_{i-1,i}^{k} = I_{i}^{k} + I_{i,i+1}^{K} \quad 2.18$$

$$V_{i}^{k} = V_{i-1}^{k} - Z_{i-1}, iI_{i-1,i}^{k-1} \quad 2.19$$

Power Loss Calculation

The power loss in the distribution line can be calculated as

$$P_{loss(i,i+1)} = |I_i| R_{i,i+1} = \frac{P_i^2 + Q_i^2}{|V_i^2|} R_{i,i+1} \quad 2.20$$

$$Q_{loss(i,i+1)} = |I_i| 2X_{i,i+1} = \frac{P_i^2 + Q_i^2}{|V_i^2|} X_{i,i+1} \quad 2.21$$

$$P_{loss} = \sum_{i=1}^{N} P_{loss(i.i+1)} \quad 2.22$$

$$Q_{loss} = \sum_{i=1}^{N} Q_{loss(i.i+1)} \quad 2.23$$

Voltage Drop Calculation

The voltage drops exist in each part of the power system from generating to the customer's meter. Voltage drop in the distribution system can be calculated as:(B. Singh and M. K. Yadav, 2018)

$$\Delta V = \sqrt{3} \times \sum_{i=1}^{n} I_i (R_i \cos\theta + X_i \sin\theta)\, L_i \quad 2.24$$

Where: -

I_i Portion current on line (A)

θ Angle between current and voltage

R_i Resistance of the line (Ohm/km)

X_i Reactance of the line (Ohm/km)

N Number of portions

L_i Portion length of the line (km)

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

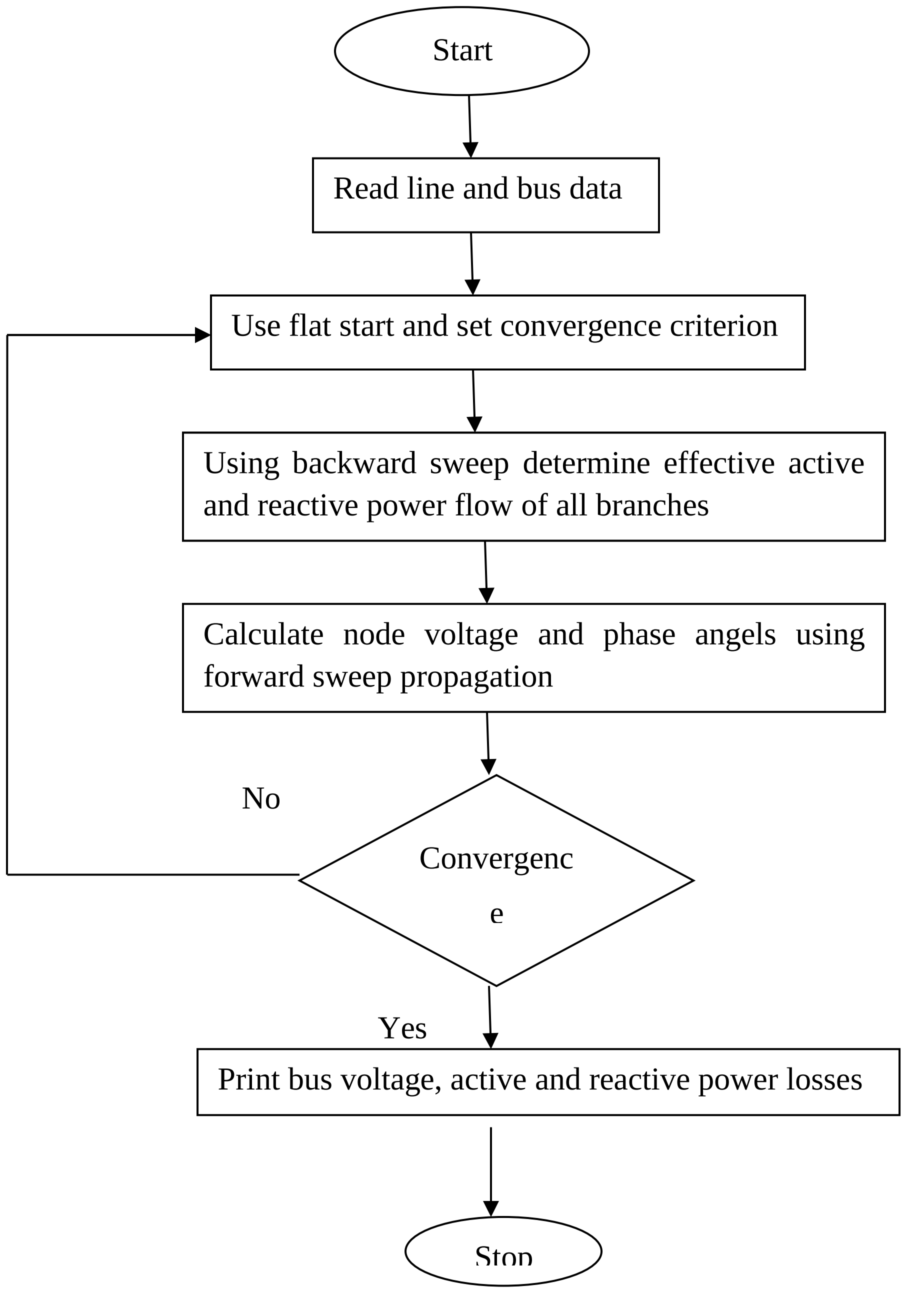

Figure 2.6 Flow chart for forward backward sweep method

2.9 Related Literature

Several researchers have put forth various approaches to address the issue of voltage drop and power loss in distribution systems.

(T. Yuvaraj, K. R. Devabalaji, and K. Ravi, 2015)Focused on determining the optimal size and location of D-STATCOM using the harmony search technique Power loss minimization was treated as a single objective function for optimization. The proposed method was evaluated using the IEEE 33-bus system and involved a direct approach utilizing the BIBC matrix for load flow analysis. The study compared the annual total loss of the distribution system before and after the installation of D-STATCOM. The results indicated a significant reduction in both real and reactive power losses, with a percentage reduction of 28.97% and 28.67% respectively. However, a challenge with this system is the requirement for a large inverter to store the highly variable solar energy and its maintenance. This issue could potentially be addressed by the government by constructing solar grids in parallel to the existing grids.

In the study conducted by (Charles, 2013), an approach based on GA-IPSO (Genetic Algorithm and Improved Particle Swarm Optimization) was presented. The approach employed a combined sensitivity factor analogy to determine the optimal location and size of multi-type Distributed Generation (DG) units within the IEEE 57-bus test system. The main objectives were to minimize power loss and improve the voltage profile of the system. The author demonstrated that the introduction of DGs into the network led to a reduction in system power loss and voltage drop, up to a certain optimal number of DG units. However, further inclusion of DG units beyond this optimal number resulted in an increase in system loss and voltage deviation beyond acceptable limits. It should be noted that the study did not consider the impact of DG on protection coordination, the specific type of DG technology, or feasibility issues.

In the study conducted by (Satrio, 2018), a proposed method involved feeder reconfiguration along with the addition of new distribution transformers to mitigate voltage drop and distribution loss. While this approach demonstrated some reduction in loss and voltage drop, it did not consider the cost implications of adding transformers and tie switches. The cost of these additional components could result in a significantly long payback period, making the overall approach potentially cost-ineffective.

In their paper, (P. Kumarasundari and Dr. Sujatha Balaraman,, 2019) discuss the enhancement of voltage profile and reduction of power loss through the optimal placement of Distributed Generation (DG) and Distribution Static Synchronous Compensator (D-STATCOM) in distribution systems. Traditional load flow models such as Gauss-Seidel, Newton-Raphson, and Fast-Decoupled methods are not suitable for distribution systems due to their high R/X ratios. Therefore, the authors employ a Direct Load Flow (DLF) analysis specifically formulated for distribution systems. For their study, they consider a 12.6 kV, 100 MVA base MVA IEEE 69 bus radial distribution systems as the test system. To determine the optimal placement, the Loss Sensitivity Factor (LSF) is utilized, which helps identify the most suitable locations for DG and D-STATCOM within the distribution network. The size of the D-STATCOM and DG is determined based on the number of buses violating limits, and the injected reactive power should not exceed the reactive power demand of the respective bus. Based on the results obtained, the authors conclude that placing both D-STATCOM and DG at the same bus yields improvements in the overall voltage profile of the network and minimizes the total real and reactive power losses.

In their study, (Amin, Amal, Salah Kamel, Ali Selim, and LoaiNasrat., 2019) introduce a hybrid analytical-coyote optimization technique (COA) for determining the optimal location and sizing of Distribution Static Synchronous Compensators (DSTATCOMs). The primary objective is to enhance voltage profiles and minimize active power losses while considering operational constraints. The analytical technique is employed to determine the appropriate sizes of DSTATCOMs, while the COA is utilized to identify suitable locations within the Radial Distribution System (RDS). However, despite the improvement in voltage profiles achieved through this approach; the results do not meet the acceptable range specified by IEEE standards.

The reviewed works of literature state different methods for an optimal allocation problem. Thus, studies have certain limitations like single objective function, long algorithm simulation time, not clearly present the necessary network constraints, and other associated benefits have not been considered while solving the location and sizing problems. This research fills the gap of previous works in the area of optimal placement and sizing of D-STATCOM like multi-objective optimization function, fast convergence characteristics of PSO algorithm.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Introduction

The electrical power distribution system is the largest component of the power system. It consists of loads, linked equipment, distribution feeders, and distribution transformers. The power flows through distribution feeders, which are then used to provide clients with the necessary power through distribution transformers. The clients need a sufficient amount of power to carry out their daily tasks. The power loss and voltage drop during transportation, however, provide the biggest challenge to the distributed power delivery to clients.

In this thesis, the first step was identifying the problem toward solving the public problem. Following that, the work of other writers was collected, including articles, journals, books, and papers on similar subjects, to find solutions tour challenges. The problem identified in the problem statement was voltage drop and power loss in distribution substations. To gain a better understanding of methods for reducing this power loss in distribution networks and improving voltage profile, a thorough literature/review of the related literature study was performed. For the case study, data was collected and analyzed. The data obtained was organized in such a way that it could be used for distribution power loss minimization and voltage profile enhancement implications. Then Load flow analysis was done for the network of Adama distribution substation for Welenchiti R_7.2 feeder both at base case operating conditions and after placement of D-STATCOM in the weak bus by identifying using particle swarm optimization algorithm and bus voltage stability index using MATLAB software. The aim of this analysis is to know the effectiveness of D_STATCOM for power loss minimization, and bus voltage profile improvement of the Welenchiti R_7.2 feeder in the Adama distribution substation. The ways followed to conduct this work start from identifying the problem up to simulating the network with optimal location and sizing of D-STATCOM.

3.2 Data collection

There are two types of data collection methods: primary data collection and secondary data collection. Ethiopian Electric Utility (EEU) Adama district and Adam substation are where the majority of the data was gathered. These data have been collected using an interview and observation. The secondary data was gathered from books, journals that have been published, manufacturer's data tables, reports that have been published, etc. The information was compiled using historical substation feeder loading (peak load) data, feeder bus and line data, conductor impedance, and other significant data. Voltage was monitored using a clap meter on the secondary side of some of the most recent transformers to see if there was any voltage drop on the selected distribution feeder.

Adama distribution substation, located in the Oromiya region of the country, is among the existing substations in the EEP power system network. The power supply to this substation is sourced from Koka substation via a single 132kV transmission line. Within the substation, there are two transformers with a capacity of 132/15 KV and 2*25 MVA each, along with a mobile substation featuring a 132/15 KV, 50 MVA transformer. The 15kV side of the substation has five outgoing feeders (L1, L3, L4, L5, L7), while the 15kV side also accommodates six outgoing feeders (M1, M2, M3, M4, M5, M6).

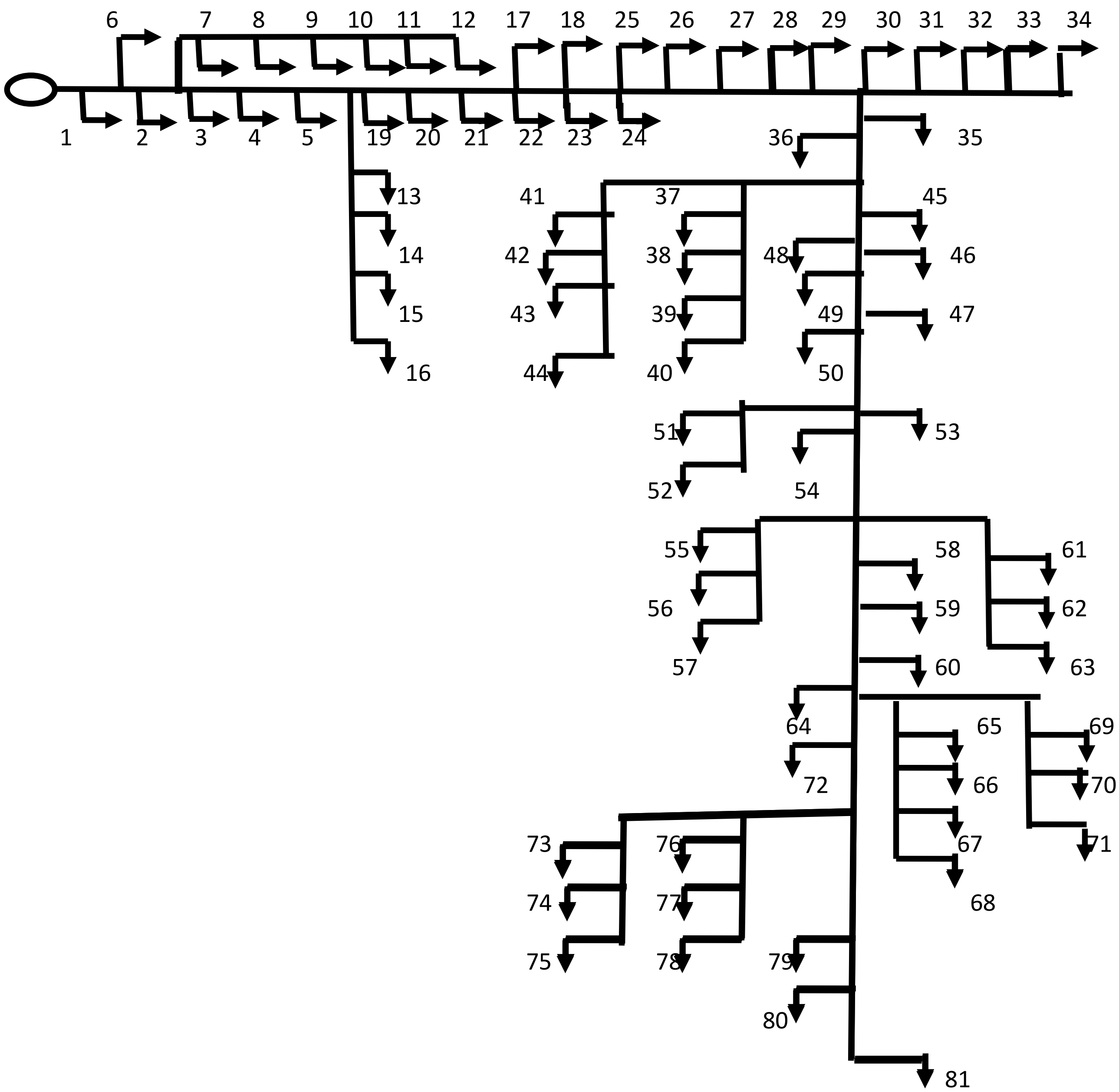

Figure 3.1 The line diagram of radial distribution feeder representation R_7.2

The single line diagram of the R_7.2 feeder is depicted in Figure 3.1 displayed above. The feeder follows a radial layout and consists of a total of 81 bus feeders. Node 1 functions as a slack bus or reference node, while the remaining 80 nodes are utilized for connecting to loads via step-down distribution transformers. The overall length of the feeder is 71.9249 kilometers, and it employs stranded conductors of AAC-25, AAC-50, and AAC-95 types. These overhead conductors serve the purpose of transmitting medium voltage (15 kV) power from the Adama substation to the distribution transformers.

3.2.1 Line data

In the collected data, the lengths of each main and branch feeder have been measured as shown in Table 1. The R_7.2 outgoing distribution feeder Adama substation has a variety of conductor types installed for its various lines.

Table 3.1 Route length parameters of Adama substation 15KV outgoing feeder R_7.2 collected from EEU.

From Bus	To Bus	Length (km)		From Bus	To Bus	Length (km)
1	2	0.493		41	42	1.35
2	3	0.469		42	43	1.72
3	4	0.03		43	44	2.44
4	5	0.184		37	45	6.46
1	6	0.107		45	46	2.39
2	7	0.4		37	47	3.9
7	8	0.01		47	48	1.25
8	9	0.223		48	49	1.14
9	10	0.152		49	50	0.826
10	11	0.181		50	51	0.051
11	12	0.131		51	52	1.17
5	13	0.289		52	53	0.149
5	14	0.338		53	54	0.25
14	15	0.658		54	55	0.675
15	16	0.428		55	56	0.113
13	17	0.305		55	57	0.139
17	18	0.295		57	58	0.338
18	19	0.418		58	59	0.369
18	20	1.03		59	60	0.398
20	21	0.46		60	61	0.0075
21	22	0.792		61	62	0.411
22	23	1		62	63	0.0075
23	24	0.475		59	64	0.387
24	25	0.259		64	65	0.067
25	26	0.18		65	66	0.643
26	27	0.06		66	67	0.0034
27	28	0.335		59	68	0.555
28	29	3.82		68	69	0.213
29	30	0.686		69	70	0.233
30	31	2.73		69	71	0.031

31	32	0.203		59	72	3.12
32	33	1.1		71	73	0.748
33	34	1.68		73	74	0.332
34	35	0.589		74	75	0.253
35	36	0.017		75	76	0.633
36	37	3.4		76	77	3.4
37	38	1.8		77	78	0.737
38	39	0.485		78	79	1.29
39	40	1.76		79	80	0.084
40	41	1.51		80	81	4.82

The material, size, configuration, length, and spacing of the wires, as well as their distance from one another, all affect the conductor's impedance, which is used in the power distribution system. The conductors used in Adama distribution feeders are stranded conductors with a 50 Hz frequency and a length of one kilometer that are also utilized to determine the inductive reactance. After that, the impedances are calculated using the following equations, with the results shown in Table 3.4.(P. Delivery and S. Member,, 1999)(P. Grid, 2015)

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

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

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

$$GMR = k \times r \tag{3.3}$$

Where: -

Za = Impedance of conductor in Ω/ *km*

Ra = Resistance of conductor in Ω/ *km*

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

GMRa = Geometric mean radius of conductor a

k = GMR factor

r = Actual conductor radius

Table3.2 the overhead conductor's parameters

Conductor Type	Conductor size (mm2)	Actual area (mm2)	Stranding and wire diameter	Overall diameter of conductor (mm)	Actual diameter (mm)	GMR (mm)	Resistance (Ω/km)
AAC	25	24.2	7/2.1	6.3	5.56	1.88	1.181
AAC	50	49.5	7/3.0	9	7.9377	2.88	0.5785
AAC	95	93.5	19/2.5	12.5	10.897	4.129	0.3085

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

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

The following conductors are used for R_7.2 outgoing feeder, which is obtained from Adama Substation SCADA drawing.

Overhead lines used for feeder R_7.2.

- AAC 95 sq. mm, AAC 50 sq. mm, AAC 25 sq. mm

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

A. For AAC-25 conductor type, the positive sequence impedance is

   $Z_{25} = 1.181 + j0.3736$ Ω/km

B. For AAC-50 conductor type, the positive sequence impedance is

   $Z_{50} = 0.5785 + j0.3470$ Ω/km

C. For AAC-95 conductor type, the positive sequence impedance is

   $Z_{95} = 0.3085 + j0.3244$ Ω/km

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

Table3.4Adama substation 15KV feeder R_7.2-line data

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

25	26	AAC95	0.05553	0.058392
26	27	AAC95	0.01851	0.019464
27	28	AAC50	0.1937975	0.11645
28	29	AAC50	2.20987	1.32554
29	30	AAC50	0.396851	0.238042
30	31	AAC95	0.731145	0.768828
31	32	AAC95	0.0626255	0.0658532
32	33	AAC25	1.2991	0.41096
33	34	AAC25	1.98408	0.627648
34	35	AAC25	0.695609	0.2200504
35	36	AAC50	0.0098345	0.005899
36	37	AAC50	1.9669	1.1798
37	38	AAC50	1.0413	0.6246
38	39	AAC50	0.2805725	0.168295
39	40	AAC25	2.07856	0.657536
40	41	AAC50	0.873535	0.52397
41	42	AAC50	0.780975	0.46845
42	43	AAC50	0.99502	0.59684
43	44	AAC50	1.41154	0.84668
37	45	AAC50	3.84124	2.24162
45	46	AAC25	2.82259	0.892904
37	47	AAC25	4.6059	1.45704
47	48	AAC25	1.47525	0.467
48	49	AAC25	1.34634	0.425904
49	50	AAC25	0.975506	0.3085936
50	51	AAC25	0.060231	0.0190536
51	52	AAC25	1.38177	0.437112
52	53	AAC25	0.175969	0.556664
53	54	AAC50	0.144625	0.08675
54	55	AAC50	0.3904875	0.234225

55	56	AAC50	0.03653705	0.039211
55	57	AAC95	0.0428815	0.0450916
57	58	AAC95	0.104273	0.1096472
58	59	AAC95	0.1138365	0.117036
59	60	AAC95	0.122783	0.1291112
60	61	AAC95	0.0231375	0.02433
61	62	AAC95	0.1267935	0.1333284
62	63	AAC95	0.0231375	0.0233
59	64	AAC50	0.2238795	0.134289
64	65	AAC50	0.0387595	0.023249
65	66	AAC50	0.3719755	0.223121
66	67	AAC50	0.019669	0.011798
59	68	AAC50	0.3210675	0.192585
68	69	AAC50	0.1232205	0.073911
69	70	AAC25	0.275173	0.0870488
69	71	AAC25	0.036611	0.0115816
59	72	AAC50	1.80492	1.08264
71	73	AAC50	0.432718	0.259556
73	74	AAC50	0.192062	0.115204
74	75	AAC50	0.1463605	0.087791
75	76	AAC50	0.3661905	0.219651
76	77	AAC25	4.0154	1.27024
77	78	AAC25	0.870397	0.2753432
78	79	AAC25	1.52349	0.481944
79	80	AAC25	0.099204	0.0313824
80	81	AAC25	5.69242	1.800752

Table3.5Adama substation 15KV feeder R_7.2 load data collected from EEU

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

3.3 Mathematical Modeling of D-STATCOM

This section demonstrates the mathematical modeling of D-STATCOM. The vast majority of distribution systems are radial in nature, with power supplied from a single side. The steady-state mathematical modeling of D-STACOM is described here, with a simple two-bus radial distribution system depicted in Figure 3.4.

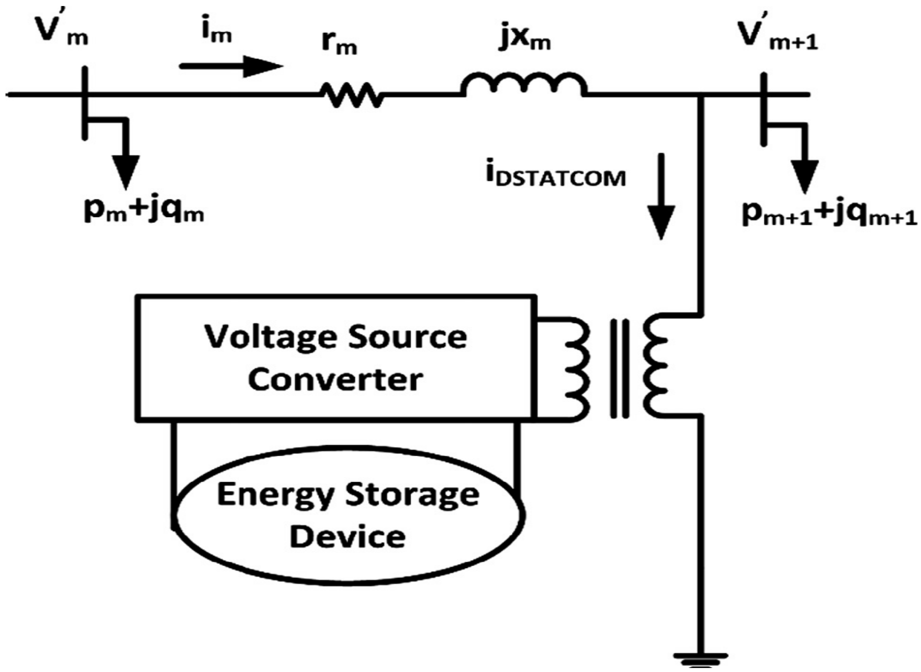

Figure 3.2 Single line diagram of two buses with DSTATCOM consideration**.**(Fahad Iqubal, Mohd Tauseef Khan, Anwar Shahzad Siddiquii, 2017)

Electrical power is often provided from a single side in the majority of distribution systems, which are typically of the radial kind. The installation of D-STATCOM at bus "m+1" is shown in Fig. 3.2. Here 'r_m' represents the line resistance and 'x_m' represents the line reactance between thebus's 'm' and 'm+ 1'. 'P_m + jq_m' and 'P_{m+1} +jq_{m+1}' represent the local loads connected at bus 'm' and 'm +1' respectively. Similarly, V_m and V_{m+1} are the voltages at the bus's 'm' and 'm+1'respectively.

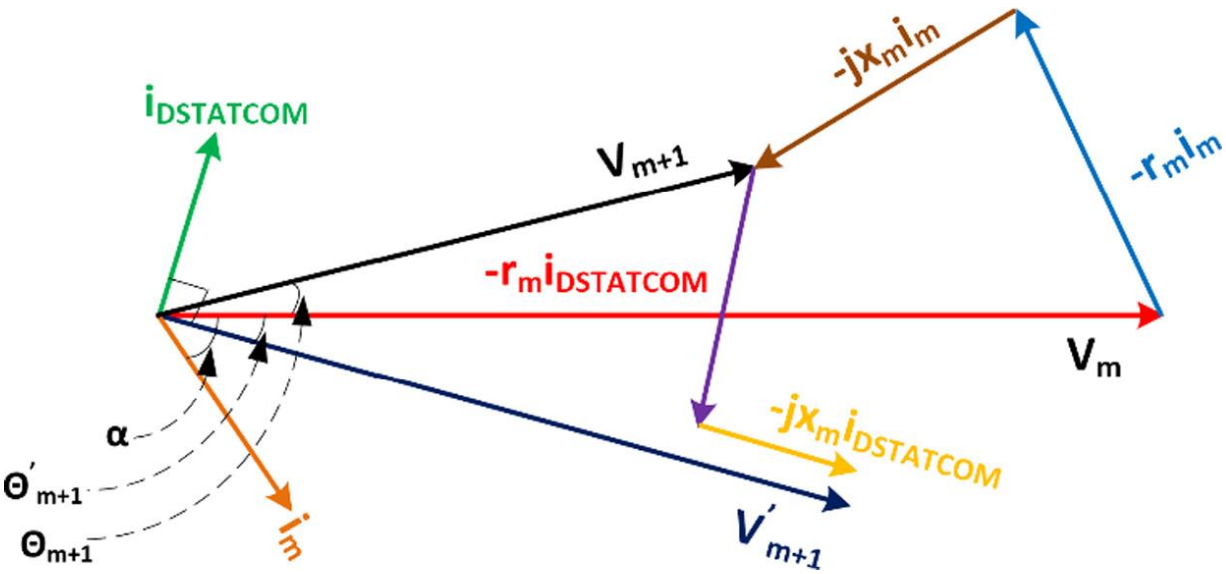

Figure 3.3 Phasor diagram of voltage and current of the system after DSTATCOM consideration (Fahad Iqubal, Mohd Tauseef Khan, Anwar Shahzad Siddiquii, 2017).

Figure 3.3 represents the phasor diagram for the two-bus system shown in figure 3.2. For a conventional radial network, the voltage values at the buses are less than 1p.u. In this case, the voltage value at bus "m+1" is assumed to be less than 1p.u. and D-STATCOM is installed in this bus to improve the voltage profile.

Considering Vm as reference bus

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

Then, using the above phasor diagram, the size of D-STATCOM is mathematically determined as follows: -

$$V'_{m+1} < \theta'_{m+1} = V_m < \theta_m - (R_m + jx_m)i_m < \alpha - (R_m + jx_m)i_{DSTATCOM} < \left(\theta'_{m+1} + \frac{\pi}{2}\right) \quad 3.4$$

Then equating real and imaginary part of equation 3.4

Real part of the equation is:

$$V'_{m+1}\cos\theta_{m+1} = Re(V_m < \theta_m) - Re(r_m i_m < \alpha) + x_m i_{D-STATCOM} \times \sin(\theta'_{m+1} + \tfrac{\pi}{2}) - r_m i_{D-STATCOM}\cos(\theta'_{m+1} + \tfrac{\pi}{2}) \quad 3.5$$

Imaginary part of the equation is:

$V'_{m+1}\,\text{Sin}\,\theta_{m+1} = Im(V_m < \theta_m) - Im(x_m i_m < \alpha) - x_m i_{DSTATCOM} \times \text{Cos}(\theta'_{m+1} + \frac{\pi}{2}) -$
$r_m i_{DSTATCOM}\,\text{Sin}(\theta'_{m+1} + \frac{\pi}{2})$ 3.6

For simplicity, let us use the notations

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

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

C_1= r_m

C_2= x_m

D = V'_{m+1}

U =$i_{DSTATCOM}$

W =θ'_{m+1}

Using this notation equation 3.5 and 3.6can be written as becomes

$$D\cos W = A + C_2 U \sin(W + \frac{\pi}{2}) - C_1 U \cos(W + \frac{\pi}{2}) \quad 3.7$$

$$D\sin W = B - C_2 U\,\text{Cos}(W + \frac{\pi}{2}) - C_1 U\,\text{Sin}(W + \frac{\pi}{2}) \quad 3.8$$

Using trigonometric identity equation 3.7 and 3.8 can be written as becomes

$$D\cos W = A + C_2 U\,\text{Cos}\,W + C_1 USinW \quad 3.9$$

$$D\sin W = B + C_2 USinW - C_1 U\,\text{Cos}\,W \quad 3.10$$

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

$$U = \frac{DcosW - A}{C_2 U\,Cos\,W + C_1 USin\,W} \quad 3.11$$

$$U = \frac{DsinW - B}{C_2 USin\,W - C_1 U\,Cos\,W} \quad 3.12$$

Then through taking $X = sinW$ and equating equation 3.5 and 3.6 we get the following most simplified quadratic equation

$$(K_2^1 + K_2^2)X^2 - (2K_1DC_1)X + \left(D^2C_1^2 - K_2^2\right) = 0 \quad 3.13$$

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

The solution of Equation 3.13can be written as become

$$X = \frac{-b\pm\sqrt{\varphi}}{2a} \quad 3.14$$

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

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

As proven with the aid of using equation 3.14, there are two roots for X and therefore, two values are calculated for the variables W and U, but only one is acceptable. To determine the correct answer, these roots are examined under boundary conditions in the load flow results i.e., if the value of D=Vm+1, then U=$i_{D\text{-}STATCOM}$=0 and the angle before compensation and after compensation become equal. This implies that D-STATCOM is neither generating nor absorbing any reactive power.

Then the root of equation $X = \frac{-b+\sqrt{\varphi}}{2a}$ is selected for correct answer for equation 3.14.

$$\mathrm{W} = \theta_{m+1} = \sin^{-1} X \quad 3.15$$

Then at bus 'm+1' the injected current, voltage and reactive power will be the following

$$V'_{m+1} = V'_{m+1} < \theta'_{m+1} \quad 3.16$$

$$i_{DSTATCOM} = i_{DSTATCOM} < \left(\theta'_{m+1} + \frac{\pi}{2}\right) \quad 3.17$$

$$\mathbf{j}\mathrm{q}_{\mathrm{D-STATCOM}} = V'_{m+1}\mathrm{i}^*_{\mathrm{D-STATCOM}} \quad 3.18$$

Where, * represents conjugate of complex variable

3.4 Optimal Sizing & Location of D-STATCOM

The thesis achieved the overall objectives of voltage profile enhancement, voltage stability and power loss minimization using particle swarm optimization algorithms. The voltage sensitivity factor and particle swarm optimization are utilized to determine the available space for search. The voltage sensitivity factor's allocation to possible buses for the best D-STATCOM placement is the first prerequisite. The optimum D-STATCOM sizing was determined in the second condition using PSO and the new best system. Finally, the power distribution system expects the system to accomplish a number of limits within the multi-objective function from a range of various objective functions. The D-STATCOM sizing randomly created switching condition is also handled by the procedures. After when using D-STATCOM, all the buses' voltages should be between 0.95 and 1.05 Pu, which is the allowable range of deviations. The ideal location for D-STATCOM depends on the allowable voltage variation range and the overall system losses.

3.4.1 Problem Formulation

Different targets may be taken into consideration in an optimization problem. In this study, the objective function considers three terms, and the optimizer is utilized to optimize all three terms. Lowering active and reactive losses, enhancing the voltage profile, and increasing voltage stability are all goals of the study. The goal function is then applied to each notion, taking the weighting coefficients into consideration. The first term in the objective function is system loss, which is defined in the following subsection.

- **Power loss**

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

$$f_1 = \sum_{i=1}^{nb} R_i * i_i^2 \qquad 3.19$$

Where: -

f_1: is objective function representing active power loss

R_i : is the line resistance of branch i,

i_i: is the current of line i

nb: is the number of system branches

$$Q_{loss} = \sum_{i=1}^{nb} x_i * i_i^2 \quad 3.20$$

Where: -

Q_{loss}: is the reactive power loss

x_i : is the reactance of line i

$\boldsymbol{i_i}$: is the current of line i

nb: is the number of system branches

- **Voltage Profile enhancement**

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

$$f_2 = \sum_{i=1}^{n_{bus}} (v_{norm} - v_i)^2 \quad 3.21$$

Where: -

f_2 : is the objective function for voltage profile improvement

v_{norm}: is the nominal voltage of the system which is equal to 1 p.u

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

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

- **Voltage stability Improvement**

The level of power system security is checked using a variety of indices. In this study, PSO is used to determine the optimal location of D-STATCOM. The node that has a greater chance to suffer voltage collapse is identified in this part using a new steady state voltage stability index. Equation 3.22 is used to calculate each node's voltage stability index. The voltage collapse phenomenon will begin at the weakest node, which is the node with the low VSI value. The load flow for each bus in the specified system is used to compute the VSI, and the results are organized in ascending order. The VSI of nodes should be increased to prevent the possibility of voltage collapse because the VSIs determine the order in which the buses are to be considered for D-STATCOM allocation.(Nebiyu Yisaye Elias Mandefro, and Belachew Bantyirga, 2020)

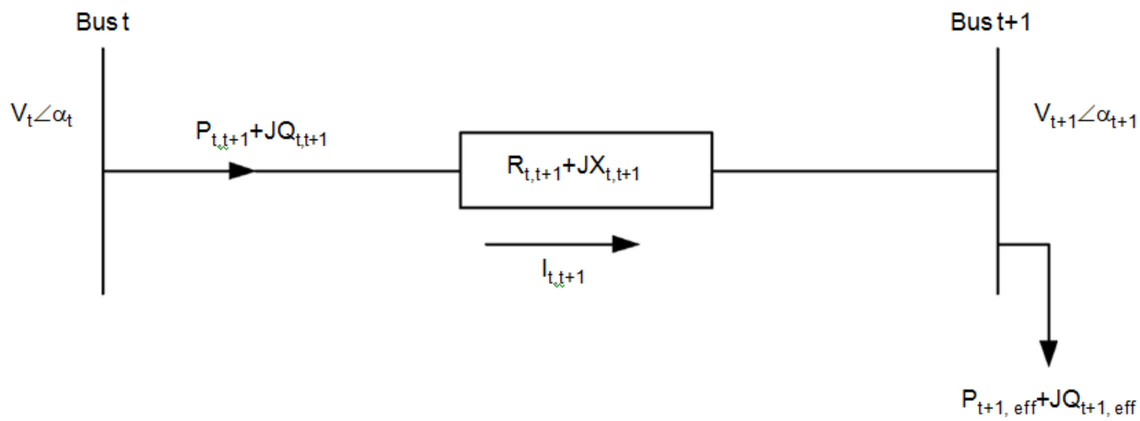

Figure 3.4 Two-bus systems for VSI analysis

$$VSI(t+1) = |V_t|^4 - 4[P_{t+1,eff} \times X_t - Q_{t+1,eff} \times R_t]^2 - 4[P_{t+1,eff} \times R_t + Q_{t+1} \times X_t]|V_t|^2 \quad 3.22$$

$$F_3 = \min(VSI(t+1)) \quad 3.23$$

Where: -

F_3: is the objective function for voltage stability index.

VSI (t+1): is the voltage stability index at bus t+1.

tand t+1: are the sending and receiving bus number.

$P_{t+1,eff}$And$Q_{t+1,eff}$: are active and reactive power demands at bus t+1, respectively.

V_t:is the voltage of the sending bus.

R_t AndX_t: are the resistance and reactance of branch t.

The mathematical formulation of the general objective function (F) is given by

$$minimize\ (F) = \min\left(W_1 \times F_1 + W_2 \times F_2 + W_3 \times \frac{1}{F_3}\right) \quad 3.24$$

Where$W_1, W_2$and $W_3$are weighting coefficients that are determined considering the importance of the three objectives and also $\sum_{n+1}^{3} W_n = 1$

3.4.2 System Constraint

Voltage deviation limit

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

$$V_m^{min} \leq |V_m| \leq V_m^{max} \qquad 3.25$$

The system voltage is constrained with $0.95 \leq Vm \leq 1.05$ Pu

Reactive power compensation

The distribution static compensator's size shouldn't be either small or too big in comparison to the load value to achieve the best result. The lower and maximum constraints for the reactive power injection by D-STATCOM into the system are as follows.

$$Q_{min} \leq Q_{DSTATCOM} \leq Q_{max} \qquad 3.26$$

3.5 PSO Algorithm Parameters

The PSO algorithm's performance may be impacted by several of its settings. The effectiveness of the PSO technique for any particular optimization issue is significantly influenced by a few of these parameter values and options, but a few others have little to no effect. (R. Vemana and Dr. M. Sridhar, 2013)

The following are the basic PSO parameters

Swarm Size: The population size or swarm size is defined as the number of particles (n) in the swarm. The search space can be covered more thoroughly in a single iteration when there is a huge swarm. The number of iterations necessary to get a satisfactory optimization result can be decreased by using more particles. On the other hand, a large number of particles make computing more complex and time-consuming for iteration that follows.

Particle Velocity: is one of the PSO algorithm's derivative techniques. The borders place restrictions on its value. The fitness is influenced by the parameters Vmax and Vmin, which specify which regions, should be searched between the current and objective locations. The solution may not be optimal because the particles move in larger phases. Similar to this, it takes longer for particles to enter suitable solutions if there are too few of them.

Random Numbers: The uniform random values are in the range [0, 1]. They help in achieving the stochastic behavior of PSO.

Inertia Weight: It's a control parameter that controls the relationship between the present velocity and the velocity that existed before.

Particle Best ($Pbest$): Each particle in Pbest memories its own event, which is conceptually akin to autobiographical memory. A particle compares its current fitness value to the best value it has ever attained at any point in time so far as it moves across the search space. The best position that has thus far been connected to the best fitness is referred to as the individual best or particle best. Each particle in the swarm's Pbest can be determined and updated during the search.

Global Best ($gbest$): Among all of the individual Pbest of the particles, it is the best position so far attained.

Termination Criterion: After the first procedure, the assessment steps are subjected to multiple iterations and objective function limits steps are subjected to multiple iterations and objective function limits after the first procedure until a stopping criterion is satisfied. The stopping condition is often met by reaching a predetermined maximum number of iterations or a specific level of accuracy in the answer.

3.5.1 Procedure for Implementation of Particle Swarm Optimization

The PSO approach can be broken down into the following steps

Step 1: Initialization: Create a population (array) of particles with random positions and velocities on d dimensions in the problem space.

Step 2: For each particle, assess the objective optimization fitness function in d variables.

Step 3: The particle's Pbest should be contrasted with the particle's fitness assessment. If the current value is better than Pbest, set the Pbest value to the current value and the Pbest location to the current location in d-dimensional space.

Step 4: Evaluate your level of fitness in comparison to the population’s highest level. Gbest is reset to the array index and value of the current particle if the value is better than gbest.

Step 5: Change the particle's velocity and position using equations 3.27 and 3.28, respectively:

$$V_i^{k+1} = \omega * V_i^k + C_1 * rand1\left(Pbest_i - X_i^k\right) + C_2 * rand2\left(gbest_i - X_i^k\right) \qquad 3.27$$

$$X_i^{K+1} = X_i^k + V_i^{k+1} \qquad 3.28$$

Where: -

V_i^k: is the ith velocity component at iteration k,

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

rand: is random number between 0 and 1,

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

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

gbest_i : is the global best position in the ith dimension,

And ω: is the inertia weight.

Step 6: Iteration updating: Update the iteration counter.

Step 7: check stopping criteria.

Step 8: if stopping criteria meets iteration stops and the PSO's best solution is the latest particle created.

Flow charts of the particle swarm optimization for the system

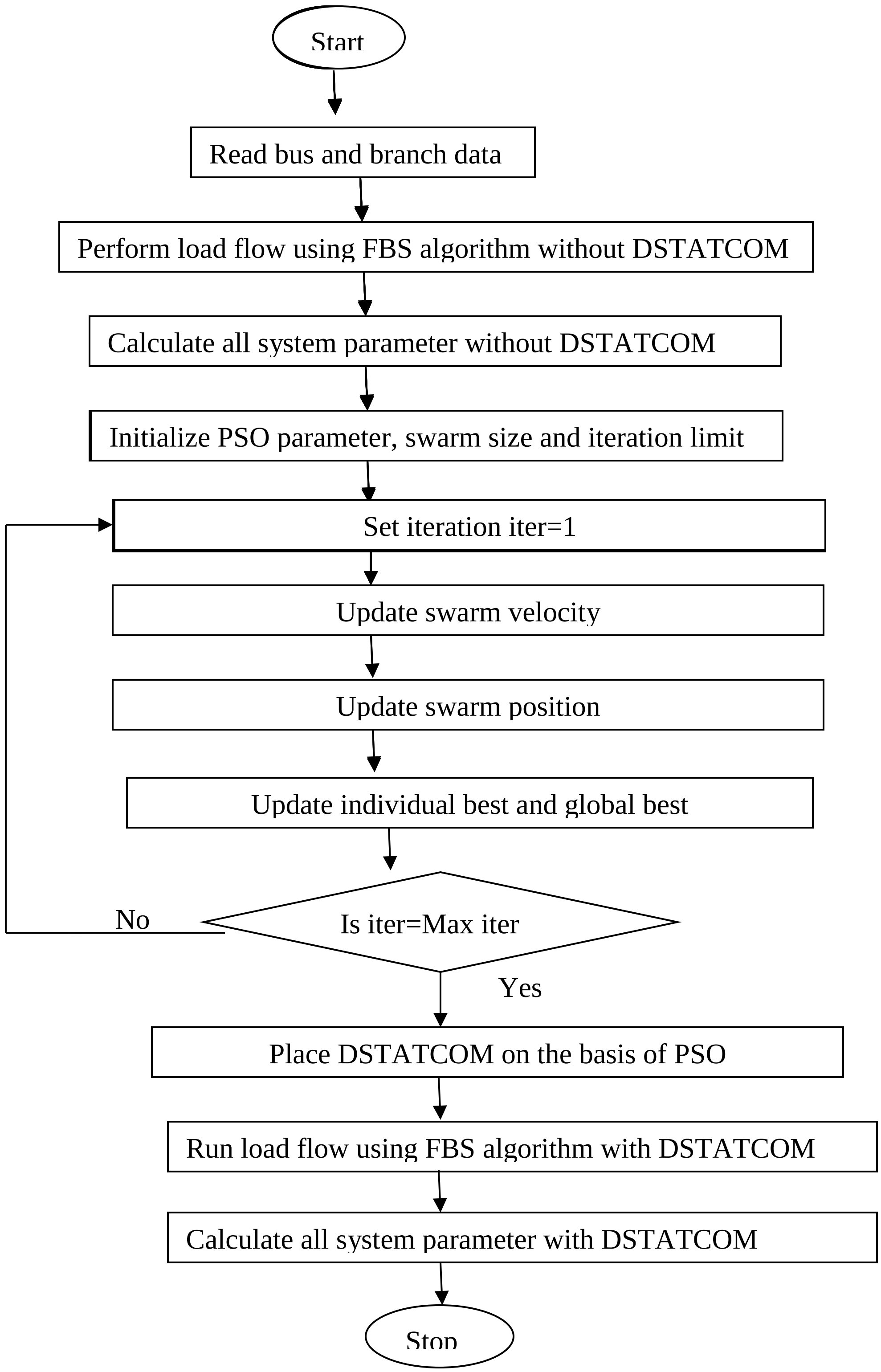

Figure 3.5 Flow charts of the particle swarm optimization for the system

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Introduction

This chapter deals with the results and its detailed discussions based on the collected data in the previous chapter and achieved with the help of the algorithm developed earlier. Power losses and voltage profile improvement are the main concern in the existing Welenchiti distribution network with specific feeder called R_7.2 having 81 buses. The PSO algorithm-based power losses and voltage profile enhancement optimization problem was implemented using MATLAB R2018 programming language.

4.2 System without D-STATCOM Installation (Base Case)

In this case, the voltage profiles at each bus and the active and reactive power losses in each line have been determined using backward/forward sweep load flow analysis without the help of any D-STATCOM. The obtained base case power losses are shown in Table 4.1, while the network's base case voltage profiles and corresponding voltage stability index values obtained from the nominal value (1 p.u). The minimum voltage of the feeder under consideration is 0.69654p.u at bus number 81, which is lower than the lower threshold limit (0.95p.u.). The feeder's voltage profile is affected by the load on the line and the distance traveled. As can be seen, voltage drops get worse as the feeder length gets longer. The minimal bus voltage stability index, based on the simulation results, is 0.23537p.u in the absence of a compensation device. The radial distribution system could experience voltage collapse due to low voltage stability, which would disrupt the system. To prevent voltage collapse and increase system security in radial distribution systems, the voltage stability index value should be increased as much as possible. The active power loss and reactive power loss in each branch is determined using forward-backward load flow algorithm in MATLAB software. The total real and reactive power losses of the given system under base case are 2511.1KW and1374.5kVAr respectively.

Table 4.1 Base Case Power Losses

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

28	29	360.8369	216.4397	68	69	1.0980	0.6586
29	30	60.9161	36.5391	69	70	0.0004	0.0001
30	31	112.2298	118.0141	69	71	0.2186	0.0692
31	32	9.0054	9.4696	59	72	0.0115	0.0069
32	33	186.8080	59.0952	71	73	1.9510	1.1700
33	34	283.7650	89.7668	73	74	0.8660	0.5194
34	35	95.0785	30.0773	74	75	0.5639	0.3383
35	36	1.2484	0.7488	75	76	0.3314	0.1988
36	37	169.9327	101.9303	76	77	3.0466	0.9637
37	38	0.1715	0.1029	77	78	0.2613	0.0826
38	39	0.0462	0.0277	78	79	0.4574	0.1447
39	40	0.2363	0.0747	79	80	0.0255	0.0081
40	41	0.0632	0.0379	80	81	0	0

4.3 System with D-STATCOM Installation

It is observed that all the buses are in the state of better voltage profile. On the other hand, based on table 4.2, the total active and reactive power losses of the network are 229.0662KW (i.e., percentage of reduction is 90.88%) and 126.5238KVar (i.e., percentage of reduction is 90.79%) respectively. The optimal size of D-STATCOM is 999.8232kVAr located at bus number 37.

Table 4.2 Power Losses after D-STATCOM placement

FROM BUS	TO BUS	P_LOSS kW	Q_LOSS kVar	FROM BUS	TO BUS	P_LOSS kW	Q_LOSS kVar
1	2	4.5792	4.8140	41	42	0.0065	0.0039
2	3	3.5175	3.6974	42	43	0.0047	0.0028
3	4	0.0389	0.0229	43	44	0.0067	0.0040
4	5	1.2880	1.3538	37	45	0.0349	0.0204
1	6	0.0003	0.0003	45	46	0.0256	0.0081
2	7	0.0501	0.0301	37	47	30.5274	9.6571

7	8	0.0001	0.0001	47	48	9.5967	3.0379
8	9	0.0073	0.0077	48	49	8.1114	2.5660
9	10	0.0025	0.0027	49	50	5.1779	1.6380
10	11	0.0019	0.0020	50	51	0.2936	0.0929
11	12	0.0003	0.0004	51	52	6.5884	2.0842
5	13	1.7792	1.8709	52	53	0.8206	2.5960
5	14	0.0043	0.0046	53	54	0.6447	0.3867
14	15	0.0141	0.0085	54	55	1.7208	1.0322
15	16	0.0053	0.0032	55	56	0.0008	0.0009
13	17	3.4466	2.0674	55	57	0.1548	0.1627
17	18	3.3162	1.9891	57	58	0.3391	0.3566
18	19	0.0000	0.0000	58	59	0.3316	0.3409
18	20	11.0368	6.6202	59	60	0.0026	0.0027
20	21	2.5721	2.7047	60	61	0.0002	0.0002
21	22	4.4044	4.6314	61	62	0.0003	0.0003
22	23	5.4400	5.7204	62	63	0.0000	0.0000
23	24	2.5840	2.7172	59	64	0.0257	0.0154
24	25	1.3472	1.4166	64	65	0.0014	0.0008
25	26	0.8710	0.9159	65	66	0.0005	0.0003
26	27	0.2869	0.3017	66	67	0.0000	0.0000
27	28	2.9865	1.7945	59	68	0.3526	0.2115
28	29	32.4591	19.4699	68	69	0.0991	0.0594
29	30	5.3923	3.2345	69	70	0.0000	0.0000
30	31	9.9346	10.4467	69	71	0.0197	0.0062
31	32	0.7846	0.8250	59	72	0.0011	0.0006
32	33	16.2754	5.1486	71	73	0.1755	0.1052
33	34	24.6925	7.8113	73	74	0.0779	0.0467
34	35	8.2013	2.5944	74	75	0.0507	0.0304
35	36	0.1062	0.0637	75	76	0.0296	0.0177
36	37	16.0182	9.6081	76	77	0.2717	0.0860

37	38	0.0199	0.0119	77	78	0.0233	0.0074
38	39	0.0054	0.0032	78	79	0.0407	0.0129
39	40	0.0274	0.0087	79	80	0.0023	0.0007
40	41	0.0073	0.0044	80	81	0	0

4.4 Result Comparison of Base Case (without D-STATCOM) and D-STATCOM Integration

A poor voltage profile with larger voltage deviation values from the nominal value was observed in the voltage profile of the investigated feeder (R-7.2 feeder), as was shown in the previous parts of the base case and D-STATCOM integration. The minimum voltage profile at bus 81 has improved from0.69654p.u. to 0.96266 p. u, which is better than the voltage value obtained before DSTATCOM insertion and the bus voltage profile across the feeder, has also been enhanced in the required range after the installation of the optimal size of D-STATCOM at the appropriate bus. Figure 4.9 provides a general illustration of this. Similarly, to this, the power losses of the system under testing were higher before the installation of D-STATCOM and significantly decreased by about 90%. The network's overall loss is illustrated in Figures 4.10 and 4.11. Before implementing D-STATCOM, the minimum bus voltage stability index was 0.23537p.u; following DSTATCOM integration, this value increased to become 0.85879p.u. Figure 4.12 provides an illustration of the voltage stability index before and after the D-

STATCOM integration simulation result for all 81-bus system buses.

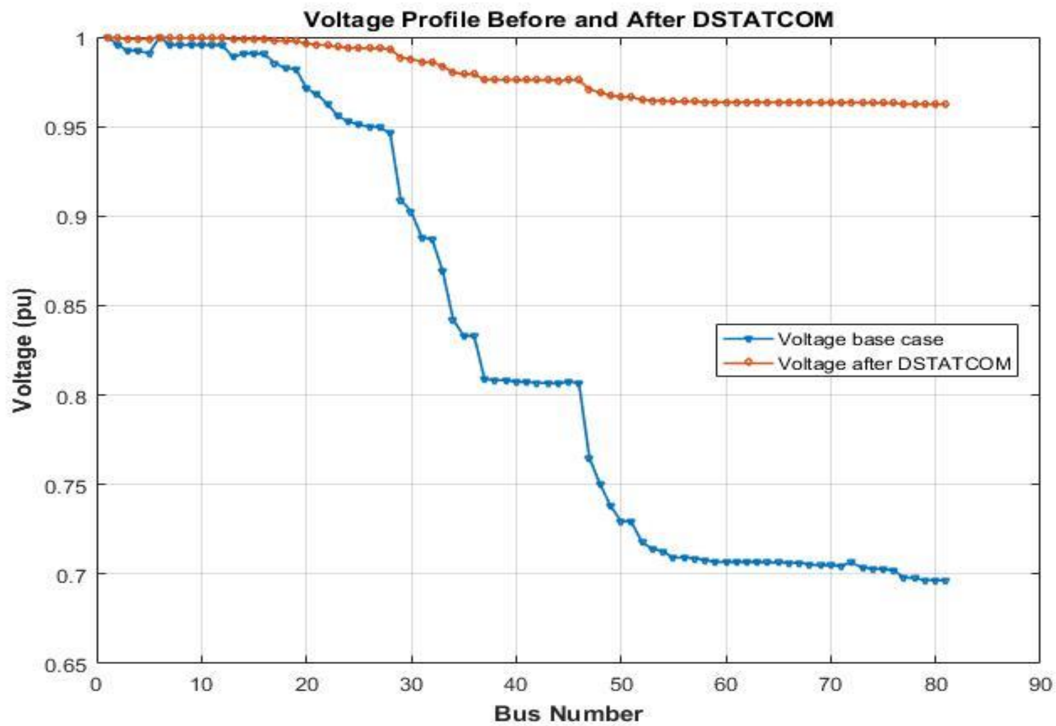

Figure 4.1 Voltage Profile of the system

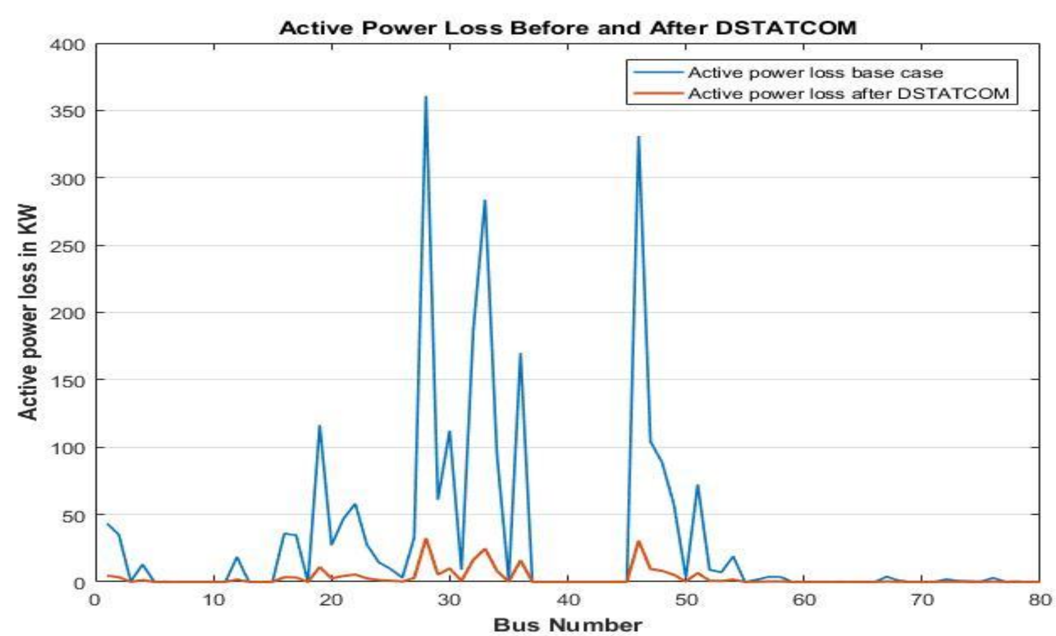

Figure 4.2 Active power Losses of the System

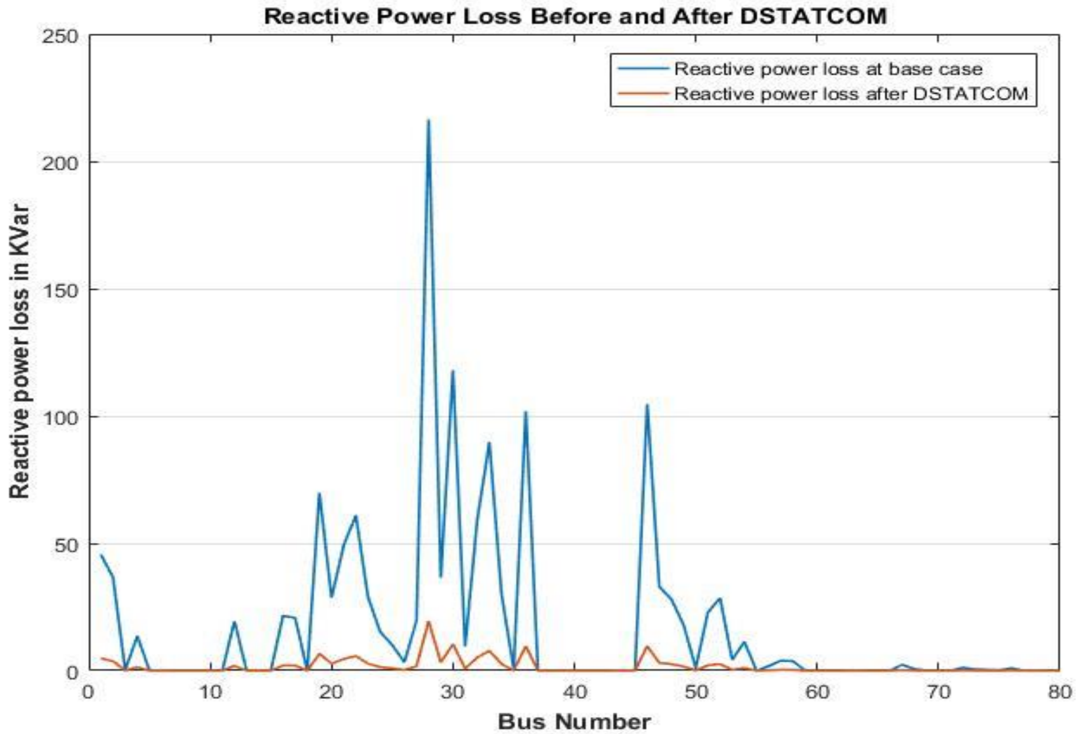

Figure 4.3 Reactive power Losses of the System

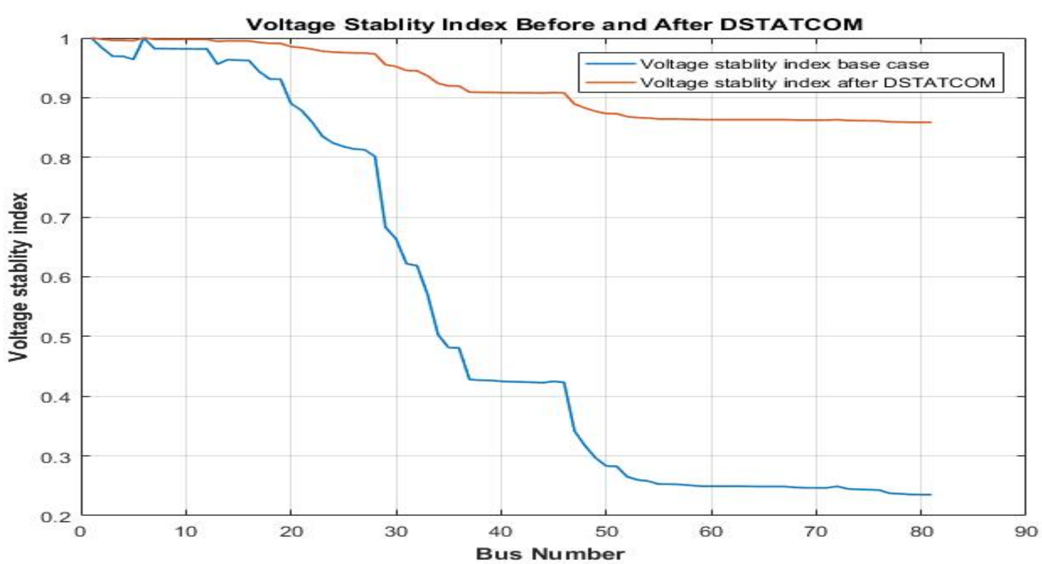

Figure 4.4 Voltage stability index of the System

Table 4.3 Summery of Welenchiti R_7.2 feeder results

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

4.5 Cost Analysis

The cost required for the D-STATCOM's successful implementation follows the determination of the device's size and location. Finding the total annual energy loss at peak load was the first step in the cost analysis.

Annual energy loss at base case

Total annual energy loss of Welenchiti R_7.2feeder = Peak power loss (MW)*8760h

= 2.511 MW * 8760 h

= 21.99 GW

The estimation of the financial loss is based on the ETB/kWh energy rates for Ethiopian Electric Utility under the revised power tariff. The cost of electricity is listed at 1.193 ETB/kWh or 1193 ETB/MWh. Using 1193 ETB/MWh, the total amount of annual financial loss resulting from power loss is approximated as follows:

Annual financial loss at base case

Annual financial loss (ETB) = Total annual energy loss*1193 ETB/MWh

=21.99 GW*1193 ETB/MWh

= 26.234 million ETB/year

Annual energy loss reduction after D-STATCOM integration

Total annual energy loss reduction of Welenchiti R_7.2feeder

= Power loss reduction (MW)*8760h

= (2.511 MW–0.229 MW) * 8760 h

= 19.99 GWh

Annual financial loss reduction after D-STATCOM integration

Annual financial loss reduction (ETB) = Total annual energy loss reduction*1193 ETBMWh
= 19.99 GWh*1193ETBMWh
= 23.8 million ETB/year

D-STATCOM integration to Welenchiti R_7.2feeder reduces the annual financial loss from 26.234 million ETB to 2.434million ETB, which is 90.72 reduction in annual energy cost. The Cost of D-STATCOM per KVAR is 244 USD including installation cost. Based on the exchange rate of Commercial bank of Ethiopia on June 16, 2023, 1 USD = 54.4683ETB. (Biniyam, 2022)

Payback period analysis
Payback period = Net investment/ Net profit
= (Cost in USD*Size D-STATCOM*Exchange Rate)/Net Profit
= (244 USD/KVAR*999.8232 KVAR*54.4683 ETB/USD)/ (23.8mil.ETB/year)
= 13.29/23.8
Payback period = 0.56year
The economic analysis show that the payback period for the initial investment cost is 0.56 year.

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This thesis work focused on the voltage drops and power losses in the distribution substation feeder. This thesis study mostly focused on using D-STATCOM to reduce power loss and enhance the voltage profile for the Welenchiti R_7.2 feeder. Welenchiti R_7.2 feeder was selected as a case study location due to its lengthy route, numerous connected transformers, and substantial growth in load. In this thesis, the maximum power loss, voltage drop, and bus voltage instability that occur in radial distribution substation feeders have been solved using the optimal size and location of D-STATCOM. The forward-backward power flow study was performed using the data gathered both before and after the installation of D-STATCOM.

The particle swarm optimization algorithm was given a multi-objective function that included enhancements to the bus voltage stability index and voltage profile. The optimum size and location of D-STATCOM were chosen via particle swarm optimization.

A forward/backward load flow technique was used to simulate the system under full load conditions both with and without the addition of D-STATCOM. Active power loss, reactive power loss, minimum voltage, and bus voltage stability index were all known as a result of the simulation. According to the simulation's outcomes, the Welenchiti R_7.2 feeder experienced total active power loss, total reactive power loss, a voltage profile, and a minimum bus voltage stability index before D-STATCOM was allocated. These values were 2511.1KW, 1374.5KVar, 0.69654 p. u and 0. 23537p.u. Respectively. Based on the simulation results, the optimal D-STATCOM size and placement for the feeder were determined to be 999.8232kVAr and bus 37, respectively.

As a result, the total active power loss, total reactive power loss, minimum voltage, and minimum bus voltage stability index were changed to 229.0662KW, 126.5238KVar, 0.96266 p. u and 0.85879p.u respectively. The percentage reductions for total active power loss and total reactive power loss were 90.88% and 90.79%, respectively. Finally, based on the results found it is possible to say that the proposed methodology is efficient in minimization of power loss and improvement of voltage profile for Welenchiti R_7.2 feeders on the side of customers and perfectly shows the advantage of applying a D-STATCOM in the distribution with a proper placing and sizing algorithm.

5.2 Recommendation

Multiple stakeholders benefit directly and indirectly from this study work. The distribution companies are the primary recipients of the results of this investigation. The Welenchiti R_7.2 feeder and Ethiopian Electric Utility will receive a number of direct benefits as a result of this thesis work, including;

- The EEU will benefit from this thesis work by having real and reactive power losses in their networks reduced. Because of the decrease in losses, they will be able to avoid paying some penalties and compensations, which will increase their profit margins and gain them more clients.
- The thesis work will also guarantee that the voltage levels at the customers are raised to the necessary levels. This will allow the EEU and EEP to save money by preventing the costs associated with compensating customers for equipment damage caused by voltage variances that are outside of allowed ranges. As a result, this improves the effectiveness and reliability of the company's operations.

5.3 Suggestion for Future work

The works listed below are suggestion to build on the study conducted for this thesis:

- Consideration of network reconfiguration with parallel DG and D-SATCOM installation can be used to undertake additional analysis.
- For the best placement and sizing of D-STATCOM, use alternative optimization algorithms such as GA, Hybrid GA-PSO, Immune, Gray Wolf, and BFOA algorithms.

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REFERENCES

al, K. e. (2021). An improved backward/forward sweep power flow Method based on network tree depth for RDS. *Electrical Systems and Inf Technol*.

Amin, Amal, Salah Kamel, Ali Selim, and LoaiNasrat. (2019). Optimal Placement of Distribution Static Compensators in Radial Distribution Systems Using Hybrid Analytical-Coyote optimization Technique. *International Middle East Power Systems Conference (MEPCON)* (pp. 982-987). IEEE.

Asare, P. (1994). *An Overview of Flexible AC Transmission Systems.*

Ayodeji Olalekan salau,Yalew Werkie Gebru and Dessalegn Bitew. (2020). Optimal network reconfigration for power loss minimization and voltage profile enhancment in distribution systems. *Heliyon*, 1-8.

B. Singh and M. K. Yadav. (2018). GA for enhancement of system performance by DG incorporated with D-STATCOM in distribution power networks. *J. Electr. Syst.Inf. Technol.*

Bedekar, A. S. Telang and P. P. (2016). Systematic approach for optimal placement and sizing of STATCOM to assess the voltage stability. *IEEE*.

Biniyam, A. (2022). STUDY ON THE POWER LOSS REDUCTION AND VOLTAGE PROFILE IMPROVEMENT OF KOTEBE DISTRIBUTION SYSTEM BY OPTIMAL PLACEMENT OF D-STATCOM USING A HYBRID OF GENETIC ALGORITHM AND PARTICLE SWARM OPTIMIZATION METHOD.

Charles, J. K. (2013). Effects of Distributed Generation penetration on system power losses and voltage profiles. *International Journal of Scientific and Research Publications*, pp12.

Chidanandappa. R, Dr.T.Ananthapadmanabha & Ranjith. H.C. (2015). Genetic Algorithm based Network Reconfiguration in Distribution Systems with Multiple DGs for Time Varying Loads. *Elsevier*, 460-467.

Desta, M. (2019). Voltage and Reactive Power Control for Power loss Minimization of Distribution Networks Case Study- (Sebeta I Substation Outgoing Feeder).

Dixon, Juan W and Morán, Luis A. (2008). Reactive power compensation technology. *AccessScience*, 1-8.

Dixon, Juan W and Morán, Luis A. (2008). Reactive power compensation technology. *Access Science*, 1-8.

F. Iqbal, M. T. Khan, and A. S. Siddiqui. (2018). Optimal placement of DG and DSTATCOM for loss reduction and voltage profile improvement. *Alexanderia Eng.J*, (pp. 755-765).

Fahad Iqubal, Mohd Tauseef Khan, Anwar Shahzad Siddiquii. (2017). Optimal Placement of DG and DSTATCOM for Loss Reduction and Voltage Profile Improvment,. *Alexandria Engineering Journal*, 755-765.

Gouvêa, S. Do Nascimento and M. M. (2017). Voltage Stability Enhancement in Power Systems with Automatic Facts Device Allocation., (pp. 60-67).

J. A. Michline Rupa and S. Ganesh. (2014). Power Flow Analysis for Radial Distribution System Using Backward/Forward Sweep Method. *International Journal of Electrical and Computer Engineering*, 1628-1632.

Kamwa, E. Ghahremani and I. (2014). Analysing the effects of different types of FACTS devices on the steady-state performance of the Hydro-Québec network., (pp. 223-249).

L.Ramesh, .P.Chowdhury and S.Chowdhury. (2009, april). Minimizaxxtion of Power Loss in Distribution systerm by Different Techniques. *Energetic, Electronic and Communication Engineering Vol:3,*, p. 4.

Mandefro, E. (2020). *Performance enhancement of distribution system using optimally allocated distributed generation.*

N.Verma, S. (2014). Comparative Study of Different Facts Devices. *JERT*, 1819-1822.

Nebiyu Yisaye Elias Mandefro, and Belachew Bantyirga. (2020). Performance Enhancement of Distribution Power System by Optimal Sizing and Sitting of Distribution Statcom. *springer*, 395-414.

P. Delivery and S. Member,. (1999). *Calculation of Overhead Transmission Line A finite Element Approach.*

P. Grid. (2015). *Calculating Sequence Impedances of Transmission Line Using PMU Measurements.*

P. Kumarasundari and Dr. Sujatha Balaraman,. (2019). VOLTAGE PROFILE AND LOSS REDUCTION ENHANCEMENT BY OPTIMAL PLACEMENT OF DG AND DSTATCOM IN DISTRIBUTION SYSTEM,. *International Research Journal of Engineering and Technology*, 7148-7153.

Piyushkumar M. Saradva, Mahesh H. Pandya. (2016). Application of DSTATCOM to Control Power Flow in Distribution Line. *IEEE*, 479-484.

R. Vemana and Dr. M. Sridhar. (2013). particle swarm optimization to optimal shunt-capacitor placement in radial distribution systems. *International Journal of Advanced Research in Electrical ,Electronics and Instrumentation Engineerin*, 4887-4895.

Reza Indra Satrio and Subiyanto. (2018). Reduction Technique of Drop Voltage and Power Losses to Improve Power Quality using ETAP Power Station Simulation Model. *Engineering International Conference (EIC2017)*, (pp. 020030-1–020030-12,).

Sanyal, S. (2021, october 31). *An Introduction to Particle Swarm Optimization (PSO) Algorithm*. Retrieved from Analytics vidhya.

Satrio, T. R. (2018). *Reduction Technique of Drop Voltage and Power Losses to Improve Power Quality using ETAP Power Station Simulation Model.*

Singh Naveen, AgnihotriPiyush. (2018). Power system stability improvement using FACTS devices. *JERT*, 171-176.

singh, E. J. (2018). Real Time Study on Technical and non-technical Losses in Distribution System and reduction techniques. *INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN TECHNOLOGY*, 276-279.

Subiyanto, R. (2018). Reduction Techniques of voltage drop and power loss to improve power quality using ETAP power station simulation model . negeria.

T. Yuvaraj, K. R. Devabalaji, and K. Ravi. (2015). l Optimal Placement and Sizing of DSTATCOM Using Harmony Search Algorithm. *Elsevier B.V.*

Taye, T. (2019). *Improvement of Distribution Feeder Loss and Voltage Profile (Case Study: Bella Substation Distribution Feeder).*

Wasiak, Irena, RozmyslawMienski, RyszardPawelek, and Piotr Gburczyk. (2007). Application of DSTATCOM compensators for mitigation of power quality disturbances in low voltage grid with distributed generation. *International Conference on Electrical Power Quality and Utilisation*, (pp. 1-6). IEEE.

Yuan, H. Minyou and C. (1994). symulated annealing algorithm of optimal reconstruction in distribution system. automation of eletric power system vol,2.

APPENDIX

Appendix A 1: Bus and Line data for Welenchiti R_7.2feeder

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

26	27	AAC95	0.01851	0.019464
27	28	AAC50	0.1937975	0.11645

28	29	AAC50	2.20987	1.32554
29	30	AAC50	0.396851	0.238042
30	31	AAC95	0.731145	0.768828
31	32	AAC95	0.0626255	0.0658532
32	33	AAC25	1.2991	0.41096
33	34	AAC25	1.98408	0.627648
34	35	AAC25	0.695609	0.2200504
35	36	AAC50	0.0098345	0.005899
36	37	AAC50	1.9669	1.1798
37	38	AAC50	1.0413	0.6246
38	39	AAC50	0.2805725	0.168295
39	40	AAC25	2.07856	0.657536
40	41	AAC50	0.873535	0.52397
41	42	AAC50	0.780975	0.46845
42	43	AAC50	0.99502	0.59684
43	44	AAC50	1.41154	0.84668
37	45	AAC50	3.84124	2.24162
45	46	AAC25	2.82259	0.892904
37	47	AAC25	4.6059	1.45704
47	48	AAC25	1.47525	0.467
48	49	AAC25	1.34634	0.425904
49	50	AAC25	0.975506	0.3085936
50	51	AAC25	0.060231	0.0190536
51	52	AAC25	1.38177	0.437112
52	53	AAC25	0.175969	0.556664
53	54	AAC50	0.144625	0.08675
54	55	AAC50	0.3904875	0.234225

55	56	AAC50	0.03653705	0.039211
55	57	AAC95	0.0428815	0.0450916
57	58	AAC95	0.104273	0.1096472
58	59	AAC95	0.1138365	0.117036
59	60	AAC95	0.122783	0.1291112
60	61	AAC95	0.0231375	0.02433
61	62	AAC95	0.1267935	0.1333284
62	63	AAC95	0.0231375	0.0233
59	64	AAC50	0.2238795	0.134289
64	65	AAC50	0.0387595	0.023249
65	66	AAC50	0.3719755	0.223121
66	67	AAC50	0.019669	0.011798
59	68	AAC50	0.3210675	0.192585
68	69	AAC50	0.1232205	0.073911
69	70	AAC25	0.275173	0.0870488
69	71	AAC25	0.036611	0.0115816
59	72	AAC50	1.80492	1.08264
71	73	AAC50	0.432718	0.259556
73	74	AAC50	0.192062	0.115204
74	75	AAC50	0.1463605	0.087791
75	76	AAC50	0.3661905	0.219651
76	77	AAC25	4.0154	1.27024
77	78	AAC25	0.870397	0.2753432
78	79	AAC25	1.52349	0.481944
79	80	AAC25	0.099204	0.0313824
80	81	AAC25	5.69242	1.800752

Appendix A-2 Load data Welenchiti R_7.2feeder

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

Appendix B MATLAB Code for Formation of BIBC Matrix

```
Function [bibc_matrix] =BIBC (linedata,busdata)
num_of_lines=length (line data (,2));
num_of_bus=length (bus data(:,1));
From node=line data (,2);
To node=line data(:,3);
connect_matrix_lf=sparse (1:num_of_lines, from node, ones (num_of_lines, 1), num_of_lines, num_of_bus);
connect_matrix_lf=sparse (1:num_of_lines, to node, ones (num_of_lines, 1), num_of_lines, num_of_bus) ;
connect_matrix_lt_lf=connect_matrix_lf+connect_matrix_lt;
connect_matrix_lt_lf1=connect_matrix_lt_lf'*connect_matrix_lt_lf;
connect_diag_mat=ones (num_of_bus)-eye (num_of_bus);
connect_diag_mat1=connect_matrix_lt_lf1.*connect_diag_mat;
final_connect_mat=triu (connect_diag_mat1);
zero_matrix=zeros (num_of_bus);
zero_matrix1=zero_matrix(:1);
for
ind=1:num_of_bus
node_order_val(:,ind)=sort([zero_matrix1(1:(num_of_bus-...
length (graph traverse (final_connect_mat, ind)))); ...
graphtraverse (final_connect_mat, ind)']);
end
node_order_final=node_order_val;
for
indr=1: length (node_order_final(1,:))
for
indc=1: length (node_order_final(1,:))
order_node=node_order_final (indr,indc);
if (order node>0)
```

```
bibc_matrix(order_node,indc)=1;
Bibc_matrix_ord(order_node,indc)=order_node;

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

Appendix C MATLAB Code for Base Case Load Flow

```
function [finalres]=LOAD_FLOW_BASE_CASE
source_num= [1];
[LINEDATA]=LINE_DATA;
BUSDATA=BUS_DATA;
baseKV=15;
baseMVA=100;
PBASE=baseMVA*1000;
VBASE=(baseKV^2)/baseMVA;
busdata_value=BUSDATA;
linedata_value=LINEDATA;
linedata_value(:,4:5)=linedata_value(:,4:5)/VBASE;
resistance_val=linedata_value(:4);
reactance_val=linedata_value(:5);
actual_imped=complex(resistance_val,reactance_val);
busdata_value(:,2:3)=(busdata_value(:,2:3)/PBASE);
imped_value=actual_imped;
[bibc_matrix] =BIBC (linedata_value, busdata_value);
```

```
bibc_matrix(source_num,:)=[];
bibc_matrix(:,source_num)=[];
final_bibc_matrix=bibc_matrix';
final_bibc_matrix=final_bibc_matrix'*diag(actual_imped);
final_dlf_matrix=final_bcbv_matrix*final_bibc_matrix;
complex_load_d=complex(busdata_value(:,2),busdata_value(:,3));% complex power load
complex_load_g=zeros(size(busdata_value,1),1);
final_load_matrix=(complex_load_d-complex_load_g);
final_load_matrix (length(source_num))=[];
initial_volt_value=ones(size(busdata_value,1)-length(source_num),1); % initial bus voltage
voltage_drop_value=initial_volt_value;
max_iter=100;
for
ind_lop=1:max_iter
%backward sweep
inject_current_data=conj(final_load_matrix./voltage_drop_value); % injected current at each
bus
   IB=final_bibc_matrix*inject_current_data; %get the cumulative injected current flowing
through each branch
old_volt=voltage_drop_value;
volt_drop_each=final_dlf_matrix*inject_current_data; %voltage drops along each branch.
voltage_drop_value=initial_volt_value-volt_drop_each;
   old_volt1=(old_volt);
new_volt=(voltage_drop_value);
error_volt_tolr=max(abs(old_volt1-new_volt));
end
final_volt_data=[ones(length(source_num),1);voltage_drop_value];
Locvoltm=find(final_volt_data>1);
final_volt_data(locvoltm)=1;
from_node=linedata_value(:,2);
to_node=linedata_value(:,3);
```

```
forind=1: length(from_node)
volt_diff_value (ind, :)=final_volt_data(from_node(ind))-final_volt_data(to_node(ind));
end
volt_diff_value1=abs(volt_diff_value);
ploss=((volt_diff_value1.^2).*resistance_val)./(abs(imped_value).*abs(imped_value))*10^5;
% Each Line Loss in kWs
loc1=find(~(isnan(ploss)));
qloss=((volt_diff_value1. ^2). *reactance Val). /(abs(imped_value).*abs(imped_value))*10^5;
% Each Line Loss in kVAr
loc2=find(~(isnan(qloss)));
total_power_loss=sum(ploss(loc1));
finalvoltage=real(final_volt_data);

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

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

f3=min(vsival);
w1=0.3;
w2=0.3;
w3=0.4;
final_obj=w1*f1+w2*f2+w3*(1/f3);
finalres{1}=final_obj;
```

```
finalres{2}=total_power_loss;
finalres{3}=finalvoltage;
finalres {4}=f2;
finalres {5}=min(vsival);
finalres {6}=ploss;
finalres{7}=qloss;
finalres{8}=vsival;
P_LOSS_kW=ploss;
Q_LOSS_kVar=qloss;
FROM_BUS_NODE=from_node;
TO_BUS_NODE=to_node;
RESULT=table (FROM_BUS_NODE,TO_BUS_NODE,P_LOSS_kW,Q_LOSS_kVar);
Finalres {20}=RESULT;
```