TRANSMISSION LINE VOLTAGE PROFILE IMPROVEMENT AND POWER LOSS REDUCTION BY OPTIMAL PLACEMENT OF STATIC SYNCHRONOUS COMPENSATOR USING TEACHING LEARNING BASED ALGORITHMS (CASE STUDY: ALABA TO BUKULUGUMA TRANSMISSION SYSTEM)

A THESIS SUBMITTED

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

In

POWER SYSTEM AND ENERGY ENGINEERING

By
MULYE GETU TSEGA

HAWASSA UNIVERSITY

HAWASSA UNIVERSITY INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

HAWASSA, (ETHIOPIA)

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By
Mulye Getu

A thesis submitted to Hawassa University, institute of technology, school of graduate studies, for the partial fulfillment of the requirement for the degree of masters of Science in power system and energy engineering.

ADVISOR: Dr. Muluneh Lemma

CO- ADVISOR: Mr. Mesifin J.

Hawassa, Ethiopia
May 2022

Declaration

I hereby declare that this MSc thesis entitled **" Transmission Line Voltage Profile Improvement and Power Loss Reduction by Optimal Placement of Static Synchronous Compensator Using Teaching Learning Based Algorithms (Case Study: Alaba to Bukuluguma Transmission System)"** is my original work and has not been presented for a degree in any other university, and will not be presented by me to any other university for similar or any other degree award, and all sources of material used for this thesis have been duly acknowledged.

Mulye Getu ____________________ ____________________

Name Signature Date

This MSc thesis entitled **"Transmission Line Voltage Profile Improvement and Power Loss Reduction by Optimal Placement of Static Synchronous Compensator Using Teaching Learning Based Algorithms (Case Study: Alaba to Bukuluguma Transmission System)"** has been submitted for examination with my approval as thesis advisor.

Dr. Muluneh Lemma ____________________ ____________________

Name Signature Date

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INSTITUTE OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

SCHOOL OF GRADUATE STUDIES

ADVISOR'S APPROVAL SHEE

This is to certify that the thesis entitled" **Transmission Line Voltage Profile Improvement and Power Loss Reduction by Optimal Placement of Static Synchronous Compensator Using Teaching Learning Based Algorithms (Case Study: Alaba to Bukuluguma Transmission System)**" submitted in partial fulfillment of the requirements for the degree of Masters with specialization in Power System and Energy Engineering, The Graduate Program of the Department of Electrical and Computer Engineering, and has been carried out by Mulye getu Tsega ID No- PGPSER/006/11, under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the department.

Dr. Muluneh Lemma .... ….. ....
Advisor Signature Date

Mr.Mesfin.J(MSc) .... ….. ....
Co-advisor Signature Date

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EXAMINER’S APPROVAL SHEET

We, the undersigned, members of the Board of Examiners of the final open defense by **Mr. Mulye Getu** Id. No: **PGposyr/006/11**, have read and evaluated his/her thesis entitled **“Transmission Line Voltage Profile Improvement and Power Loss Reduction by Optimal Placement of Static Synchronous Compensator Using Teaching Learning Based Algorithms (Case Study: Alaba to Bukuluguma Transmission System)”**, and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree.

Name	Signature	Date
________________	______________	______________
Chair Person		
Dr. Muluneh Lemma.	______________	______________
Advisor		
Mr. Mesfin.J(MSc)	______________	______________
Co- advisor		
________________	______________	______________
External Examiner		
________________	______________	______________
Internal Examiner I		
________________	______________	______________
Internal Examiner II		
________________	______________	______________
SGS Approval		

Acknowledgements

First and foremost, glory and thanks to the almighty God for the completion of this master's thesis. This thesis work would not be possible without the help of my advisor Dr. Muluneh Lemma, who has supported me by giving his invaluable guidance, encouragement, advice and suggestions throughout my MSc Education and thesis work. I also wish to express my gratitude to Mr. Mesfin Jariso, who is my co-advisor for his good comments and valuable suggestion and the Hawassa Institute of Technology, Electrical and Computer Engineering school staff members through teaching me at IOT and for their supportive characteristics. My appreciation goes to Alaba substation workers for providing important data and materials needed for this work. I heart fully thanks my mother and my friends, who have supported me throughout my education and certainly no less during my thesis work.

Abstract

The power transmission system transports electric power generated at generation plant to distribution system. The increasing power demand of customers causes the power transmission system to become stressed when connected to distribution system. This leads to voltage instability and, further to, transmission power loss, which can lead to power system malfunction and system collapse. Most bus voltages are not within acceptable limits, and the voltage index of the buses indicates that the network is prone to voltage instability issues. The objective of this thesis is to determine the best placement for a static synchronous compensator (STATCOM), which is one of the Flexible AC Transmission Systems (FACTS) devices, on the Alaba to Bukuluguma Transmission System network to minimize transmission line loss, improve voltage profile, and enhance power transfer capacity. The power flow analysis by Newton Raphson algorithm in MATLAB environment is used and Teaching Learning-based optimization techniques (TLBO) are adopted for optimal sizing and location of the device. The obtained results were compared to those reported in the literature for conventional optimization techniques. The optimal location and size of STATCOM for the Alaba to Bukuluguma transmission network were identified using the genetic algorithm (GA) and particle swarm optimization (PSO) methods accordingly, 25.8MVar at bus 6 and 25.5 MVar, at bus 5 respectively. According to the TLBO technique, bus 4 with 25MVar is the best placement and size of STATCOM in the network. The TLBO approach, as previously indicated, performs better in terms of reducing real and reactive power losses. The test system's real power loss reduction is 39.8 percent, while the reactive power loss reduction is 49.3 percent. In addition, the worst-case minimum voltage level has been enhanced from 0.878pu to 0.953pu. STATCOM control is established in this study utilizing artificial intelligence (AI) and an artificial neural network (ANN), which is based on TLBO's optimal values. In general, simulation results demonstrate that the suggested approach is effective in keeping all bus voltage magnitudes within the IEEE permissible limit while also drastically reducing power losses.

Keywords: *Loss reduction, optimal location, optimal size, Objective function, Transmission System, Voltage Stability index and voltage Profile.*

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List of Acronyms

ANN	Artificial Neural Network
ATC	Available Transfer Capability
ABC	Artificial Bee Colony
CIM	Current injection model
CDI	Critical Damping Index
D-STATCOM	Distribution Static Synchronous Compensator
DVR	Dynamic Voltage Restorer
DP	Dynamic Programming
DE	Differential Evolution
E E-STATCOM	Energy Storage Static Synchronous Compensator
EP	Evolution Programming
(FC-TCR)	Thyristor-Controlled Fixed Capacitance Reactor
FA	Firefly Algorithm
GM	Gradient Method
GA	Genetic Algorithm
GSA	Gravitational Search Algorithm
HVDC	High Voltage Direct Current
HS	Harmony Search
HNN	Hopfield Neural Network
IP	Interior Point
IPFC	Interline Power Flow Controller
LP	Linear Programming
LRA	Lagrangian Relaxation Algorithm
NM	Newton Methods

NLP	Non-Linear Programming
N-R	Newton Raphson
PIM	power injection model
PI	Proportional Integral
PSO	Particle-Swarm Optimization
PS	Pattern Search
PCC	point of Common Coupling
QP	Quadratic Programming
STATCOM	Static Synchronous Compensator
STS	Static Transfer Switch
SSSC	Series Connected Static Synchronous Compensator
SVC	Static Var Compensator
TLBO	Teaching Learning Based Optimization
TCSC	Thyristor Controlled Series Capacitor
(TC-PST)	Thyristor Controlled Phase Shifting Transformer
(TS-TCR)	Switched Capacitor Thyristor Switched Capacitor
TS	Tabu Search
UPS	Uninterrupted Power Supplies
UPFC	Unified Power Flow Controller
VSC	Voltage Source Converter
VSI	Voltage stability Index

CHAPTER ONE

1. INTRODUCTION

Electrical power system basically consists power generation system, power transmission System, power distribution system and loads or end users. The electric power generation system is a power station where the electricity is generated from various available energy sources. The generated power is stepped up and enters to the power transmission system. The basic structure of a power system is as shown in Fig1.1. It is composed of generating plants, a transmission system and distribution system. These subsystems are interconnected through transformers T1, T2 and T3.

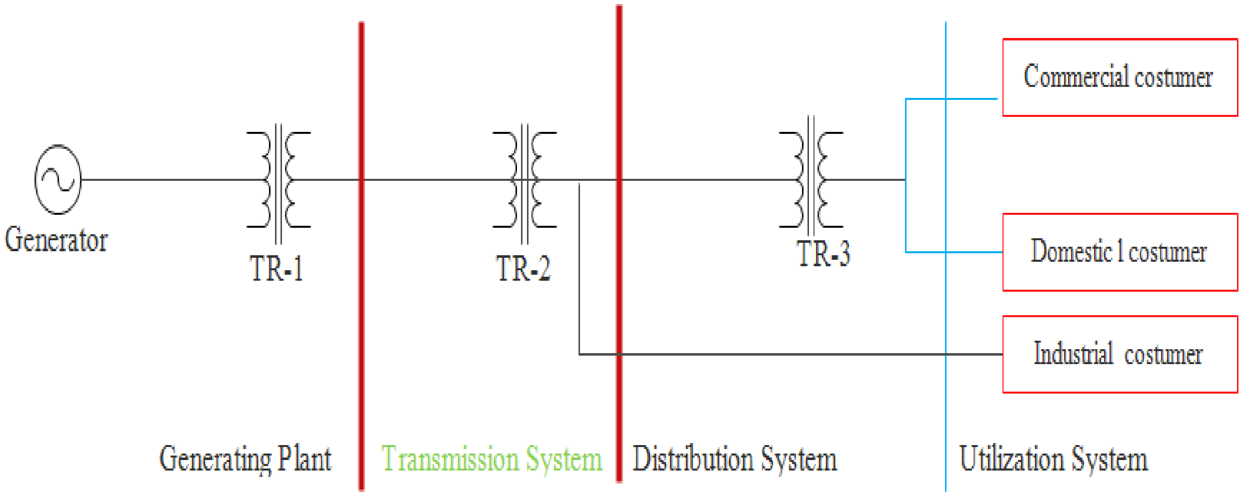


Figure.1-1: The basic structure of a power system

The electric power transmission system is the one in which the bulk power is transmitted through a long distance to the electric distribution system. The distribution system stepped down the voltage and distribute to the customers. The power transmission system connects the generation station to distribution or load centers. The load demand increment of the customer connected to distribution system affects the transmission system.

The demand for electric power among local Ethiopian Electric Power (EEP) customers has increased rapidly over the last two decades, ranging from very large corporations to small residential consumers. The country's foreign investment policy is highly tempting, and as a result, a number of new industries are springing up and running. To accommodate this large electric power demand, the present power transmission infrastructure's voltage stability and security must be upgraded. Voltage instability and power loss in the transmission system increase as a result of reactive power imbalances caused by load augmentation and power transfer constraints. Furthermore, voltage stability will fall below an acceptable level [1].

This will eventually lead to the system's collapse. Due to its complexity and the economic reasons stated building a new transmission line will not be an appropriate way to address the aforementioned difficulties in [2]. As a result, the most effective way to address this basic issue is to develop a new method of transferring data that is more efficient while still utilizing existing transmission lines.

Electromechanical equipment was used to solve problems for a few years. The equipment consisted of switching inductors or capacitor banks, as well as a phase-shifting transformer. However, due to certain equipment problems, all of this technology is not reliable or efficient enough. They are not only slow but they cannot be exchanged frequently since they wear out quickly in [3]. In this regard, adopting Flexible AC Transmission Systems (FACTS) technology is one viable solution for enhancing system operation. It increases the capacity of existing transmission lines and expands the options for power regulation in [4].

FACTS devices have two inherent benefits over more typical switching capacitor and reactor-b devices. For starters, power electronics-based voltage sources can generate and absorb reactive power internally.

Second, by facilitating both reactive and real power adjustment, they can enable independent control for real and reactive power flow. However, not all FACTS devices can do the functions indicated above, so selecting the correct ones is critical. According to [5] the IEEE defines the FACTS device as "alternating current transmission systems using power electronic-based and other static controllers to enhance and expand power transfer capabilities." The FACTS controller is defined as "a power electronic-based system and related static equipment that manages one or more alternating current transmission system characteristics" [6].

On the Alaba to Bukuluguma transmission system (AL-BTS) network, there are primarily two electric power generation plants. These are the Gilgel Gibe I and Gilgel Gibe II power plants. Gilgel Gibe I is located 245 kilometers from Alaba and has three generating units with a total capacity of 184 MW. Gilgel Gibe II hydropower plant has three producing units with a total maximum generating capacity of 420 MW and is located 75 kilometers from Alaba substation.

The transmission voltage from this power plant to the Alaba substation is 132kv. The focus of this thesis is the appropriate placement of STATCOM devices for voltage profile improvement, power loss reduction and enhances power transfer capacity in the existing Alaba to Bukuluguma transmission network. The transmission lines connecting Alaba substation to Hawassa substation II, Hawassa substation II to Hawassa substation I, Hawassa substation I to Yirgalem substation II, Yirgalem substation II to Yirgalem substation I, Yirgalem substation I to Dilla substation, Dilla substation to Hager-Mariam substation, and Hager-Mariam substation to Bukuluguma substation**.**

1.1. Overview of the case Study

The Ethiopian Electric Power (EEP) Power Transmission and Interconnected networks surrounding the system are an interesting case study for this thesis. The area's power transmission and interconnected networks are depicted in Figure 1.2, which primarily consists of Alaba, Hawassa, Yirgalem, Dilla, Hager-Mariam, and Bukuluguma buses operating at 132kV transmission voltage. The Gilgel Gibe I hydropower facility is located 245 kilometers from Alaba and has three producing units with a combined capacity of 184MW. This power plant's transmission voltage level to the Alaba substation is 132 kV, whereas the transmission voltage level from this power plant to the Alaba substation is 132 kV (from EEU/EEP).

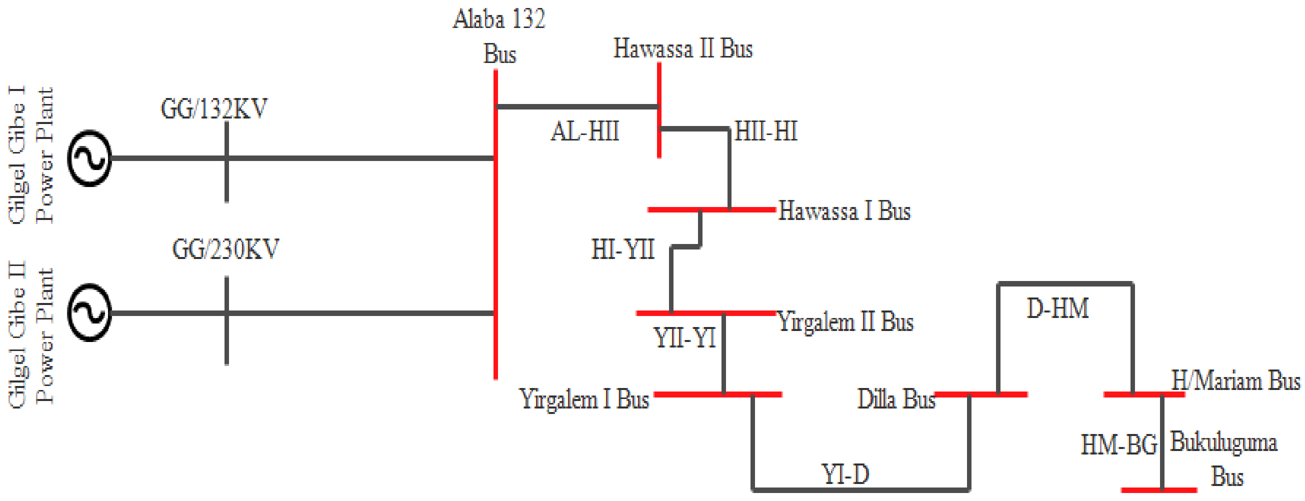


Figure 1-2: Single line diagram of the case study with interconnected networks

Where,

AL-HII**:** Alaba Bus to Hawassa II Bus
HII- HI**:** Hawassa II Bus to Hawassa I Bus
HI- YII**:** Hawassa I Bus to Yirgalem II bus
YII- YI**:** Yirgalem II Bus to Yirgalem I Bus
YI-D**:** Yirgalem I Bus to Dilla Bus
D-HM**:** Dilla Bus to H/Mariam Bus
HM-BG**:** H/Mariam Bus to Bukuluguma Bus

Due to the network topology, imbalanced supply, and lack of compensation devices in the system, the area faces a number of power issues. Because costumer power demand on the existing network grows, voltage limit violations in the area are the most significant of the problems.

The focus of this thesis will be on how to use STATCOM and its placement to keep bus voltages within the limit, enhance voltage profiles and minimize a substantial amount of loss.

1.2. Statement of the Problem

Electric power systems play important roles in the industrial and socioeconomic development of any nation. Electrical energy is generated and transported from remote generating stations to the load centers through transmission lines. These transmission lines are susceptible to losses and voltage profile problems, which affect the ability to deliver the same amount of power generated at the receiving end. This has become a problem that needs to be solved through research.

The increase in customer power demand causes the system to experience stressed conditions. This causes voltage instability and, further to, transmission power loss. As a result, transmission lines are vulnerable to losses, which have a significant impact on transmitting the required amount of power generated at the generation station to the receiving end. Transmission power loss is also a significant cost for utilities. Consequently, more transmission line losses will imbalance the energy demand and the power supply. Due to the power loss problem and poor voltage regulation problem the area in the Alaba to Bukuluguma transmission system is not receive sufficient energy from the main supply. FACTS controllers are increasingly being used in networks to address some of these concerns.

The static synchronous compensators (STATCOM) application of FACTS controllers is crucial for maintaining an appropriate voltage level in a power transmission system. Because these devices are costly, they must be put in the power system as effectively as possible. As a result, TLBO can be used in this thesis to investigate the effect of STATCOM placement on the existing network. As a consequence, this thesis will study transmission system loading margin violation and its enhancement utilizing optimally placed STATCOM on the Alaba to Bukuluguma transmission system, with the goal of improving voltage profile, minimizing power loss and enhance power transfer capacity caused by increased load demand.

1.3. Objective of the Thesis

1.3.1. General Objective

The main objective of this thesis is to minimize transmission line loss, improve voltage profile, and enhance power transfer capacity by optimal placement of STATCOM in the existing transmission network.

1.3.2. Specific objective

- To investigate performance analysis, identify transmission line losses and the voltage profile of the existing transmission network.
- To optimal size and locate STATCOM for improve voltage profile and minimize the system loss in a transmission system using TLBO.
- To compare the effects of inserting the STATCOM device on system loss minimization and voltage profile improvement.
- Developing control strategy for the proposed STATCOM based on AI technique ANN, which depends on optimum values of controller gains.

1.4. Scope of the Study

The thesis focuses on the improving voltage profiles and power loss reduction in the transmission network from Alaba to Bukuluguma transmission system by optimal placement of STATCOM using TLBO optimization.

Generally, the scopes of this thesis are: -

- A steady-state analysis of a power transmission system is performed using load flow analysis.
- Comparison of system network with and without STATCOM.
- Develop a program for optimal placement and size of the STATCOM in Matlab based on TLBO optimization techniques for power loss minimization and voltage profile improvements.
- Finally, determine the total cost loss of the system after enhancement and make a comparison of a system.

1.5. Importance of the Research

This thesis output has significant importance on measuring the existing network performance and providing solutions as well as serving as a benchmark for the prediction of the future Alaba to Bukuluguma electrical transmission network capacity.

In general, it has the following advantages: -

- Reduce the impact of power failures on consumers' and utilities' economies.
- Improved voltage profiles and reduced system loss by optimal placement of STATCOM.

1.6. Methodology

The following activities are performed in this thesis:

Literature review: A number of journals, articles, and papers on power transmission system power loss reduction, and improvement, placement of FACTS device and other related works have been reviewed.

Data collection and analysis: one-year (2013 E.C) data has been collected from the Alaba substation. The power flow analysis has been collected from the existing system. The collected data has been used to clearly analyze the problems of the system under study.

System design: The transmission system is represented using single line diagram and improved network topology placement with tie STATCOM has been developed.

1. The Newton-Raphson technique was used to examine the power flow of an existing transmission system.
2. Based on the results of this power flow analysis and the installation of STATCOM, MATLAB simulation, and a modified TLBO were used to identify the optimal size and location for voltage profile improvement and power loss minimization.
3. The objectives of the thesis are to improve Voltage profiles, power loss reduction and enhance power transfer capacity of existing transmission network.
4. Several methods for determining the best STATCOM placement for a system have been developed. Heuristic approaches, Particle Swarm Optimization, Firefly Algorithm, Bacterial Foraging Optimization Algorithm, Ant Colony Optimization, and genetic algorithms are examples of these. Modified TLBO is used in this thesis because it can generate accurate results fast.

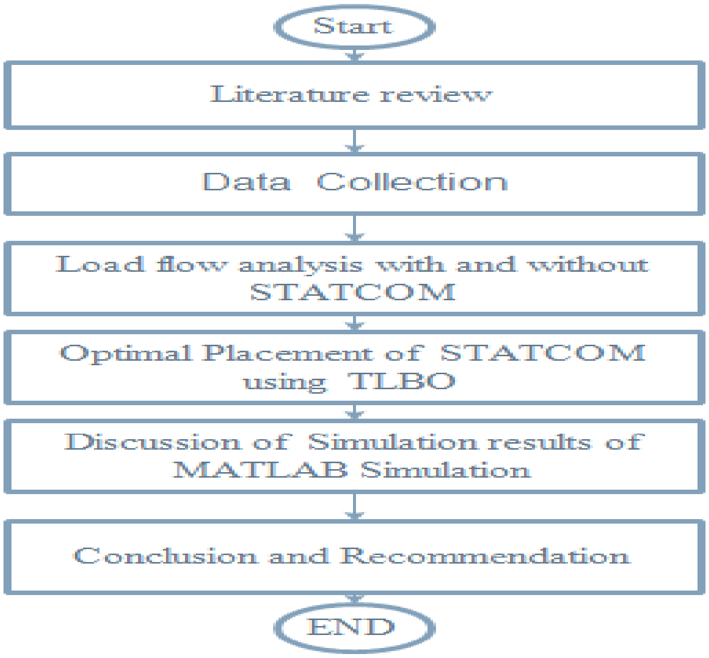


Figure 1-3: The flow chart of the thesis

Thesis Outline

Chapter 1 This chapter presents an introduction of the research work, outlines the problem statement, and gives a justification for the research work and finally the goals of the work.

Chapter 2 This chapter discusses controllers, power flow analysis, voltage stability enhancement approaches, and power loss reductions in transmission systems for optimization reasons, ANNs control method.

Chapter 3 This chapter gives the methodology followed in carrying out this research work.

Chapter 4 This chapter presents the results obtained and an analysis and discussion of the same against the objectives of the research.

Chapter 5 This chapter presents a conclusion of the work and gives recommendations and/or gaps for future research.

CHAPTER TWO

2. THEORETICAL BACKGROUND AND LITERATURE REVIEWS

2.1. INTRODUCTION

Reactive power compensators are critical in transmission system networks for minimizing network voltage magnitude deviations and losses. To achieve these goals, the optimal location and size of the compensator are critical. As a result, this chapter discusses some of the devices used in transmission systems for voltage deviation minimization and power loss reduction. The methods used to determine the optimal location and reactive compensator capacities were discussed, and the relevant literature was also reviewed.

2.1.1. Reactive power compensator

Electrical devices termed reactive power compensators absorb or inject reactive energy into the power network to increase transmission capacity. They're frequently connected at the correct places in the transmission system to improve the power network's voltage profiles and reduce losses. The parts that follow go over different types of reactive power compensators.

2.1.2. Capacitor

A shunt-compensator generates the required reactive power into the network. Capacitors connected in shunt, are placed at a bus to hold the bus voltage levels, injecting required reactive power into a network to do so. On the other hand, a capacitor connected in series is called a series compensator.

A series compensator is placed between two buses in the transmission network to control the line reactive power flow in [7].

2.1.3. Flexible Alternating Current Transmission System

FACTS are a power electronics-based system that consists of static equipment for power transmission. It improves the network's power transmission capability and controllability in [8].

FACTS is described by the Institute of Electronic and Electrical Engineering (IEEE) as equipment capable of adjusting one or more transmission network control values to improve power transfer capability and controllability. FACTS devices save money on power delivery and increase system reliability. By injecting or absorbing required reactive power into the transmission network, they improve the efficiency and quality of the system. There are several varieties of FACTS devices, including static synchronous compensator (STATCOM), SVC (static VAR compensator), UPFC (unified power flow controller), TCSC (thyristor-controlled series capacitor), and IPFC (interline power flow controller) in [9].

2.2. Application of Power Electronics in Power System

The use of sturdy devices for the control of electrical or electric power is referred to as power electronics. It's difficult to provide an exhaustive list of power electronics applications in today's world; it's made its way into practically every industry that utilizes electricity in [10].

Because of the simplicity of manufacture, these devices are now available in a wide variety of ratings and have progressively made their way into power systems. High-voltage- voltage current (HVDC) connections and FACTS devices are power electronics devices used in power systems. HVDC lines employ a different method of transmitting electrical power than FACTS controllers, which are used for reactive power adjustment and power system enhancement. Devices used in the power grid are used to enhance system power quality and are sometimes referred to as bespoke power devices, whereas devices used in the transmission system are optimized to decrease losses by balancing reactive power.

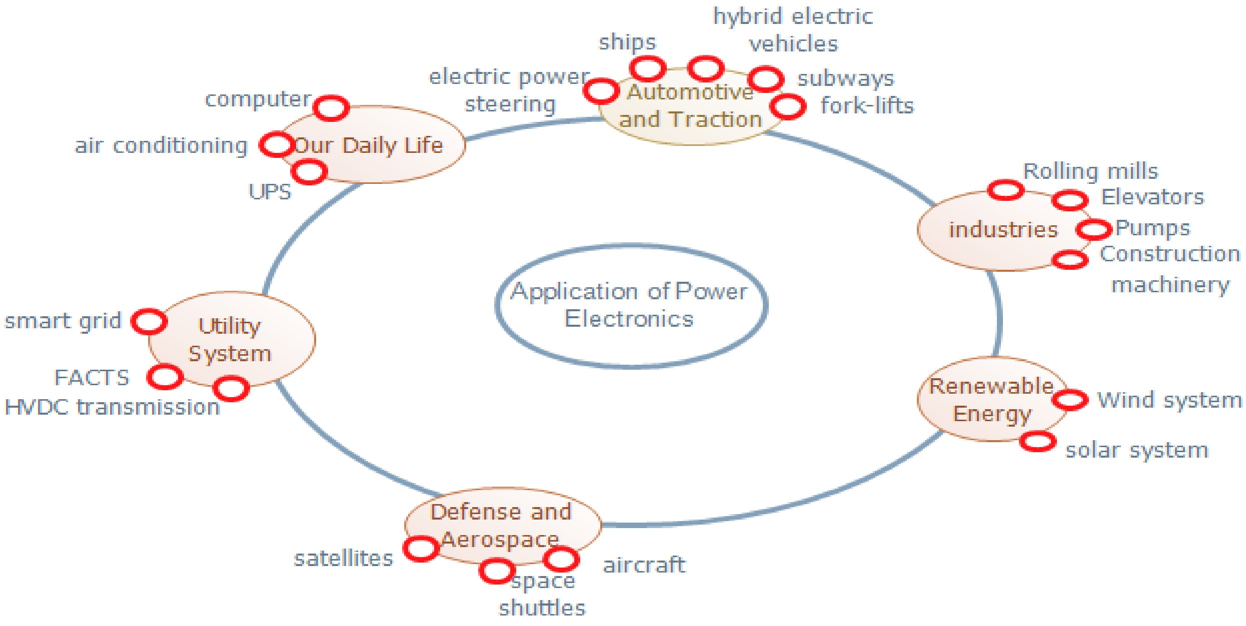


Figure 2-1: Diaspora of power electronics

They are widely utilized in the power system, and they stimulate the system's growth in a more intelligent and sustainable path. According to the statistics, power electronic converters handled at least 70% of the final electric energy used in developed nations. This implies that power electronics is important for power production, transmission, harmonics management, power supply stability, and other components of the power system.

2.2.1. Distribution Level

Power electronics controllers are used to increase transmission network stability and control power flow, while custom power devices are used to improve power quality in distribution systems. Harmonics issues, transient over-voltage damage, and equipment tripping as a result of voltage dips have all led to the use of tunable and dynamic devices to address these issues. Unlike FACTS devices, custom power devices are also put in different ways: series-connection, shunt connection, combine series-shunt connection in [11]. The type of customs devices utilized in the distribution system is discussed below:

2.2.1.1. Distribution Static Synchronous Compensator

A VSC and a tiny DC-capacitor make up distribution static synchronous compensator (D-STATCOM). Reactive power is exchanged between the distribution system and D-STATCOM in [12]. D-STATCOM is a reformation or adaption of STATCOM for use with FACTS devices on the distribution system, and it solely provides reactive power. On the distribution network, D-STATCOM is used to manage voltage during transients and voltage dips, filter the system to reduce current harmonics, and load balance. Figure 2-2 depicts D-connections STATCOM's in a distribution network.

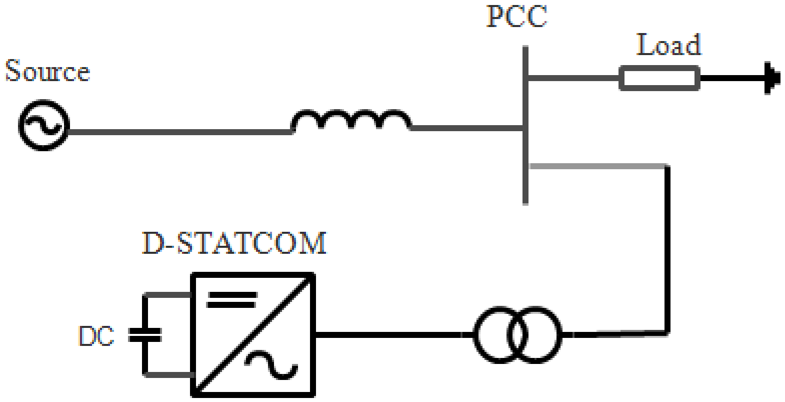


Figure 2-2: D-STATCOM on a distribution system

2.2.1.2. Energy Storage Static Synchronous Compensator

Energy storage static synchronous compensator (E E-STATCOM) is a shunt-mounted device capable of absorbing or injecting reactive and actual current. In a distribution system, Figure 2-3 demonstrates how it is connected. It has voltage source converter (VSC) as well as energy storage. This E-STATCOM model is capable of supplying real and reactive power. However, due to its limited energy storage capacity, it is unable to inject real power for an extended period. Except for its energy storage capacity, which swaps active power with the system E-STATCOM has a similar purpose to D-STATCOM in [13].

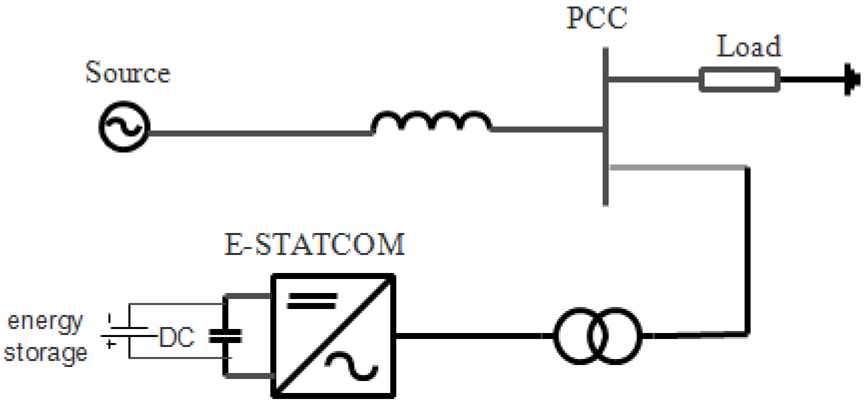


Figure 2-3: E-STATCOM on a distribution system

2.2.1.3. Dynamic Voltage Restorer

DVRs (dynamic voltage restorers) are series devices that include a voltage stabilizer (VSC) that produces injected A.C. voltages for voltage sag improvement via injection transformers. The major advantage of the usage of the DVR to reduce the voltage drop is its dynamic performance, which is not reliant on the source impedance. Likewise, it can be used to adjust for unbalanced voltage and filter voltage harmonics. The only disadvantage of DVR is the cost increase due to the installation of a sophisticated protection mechanism in the case of a short circuit malfunction in [14]. The configuration of a DVR in a distribution network is shown in Figure 2-4.

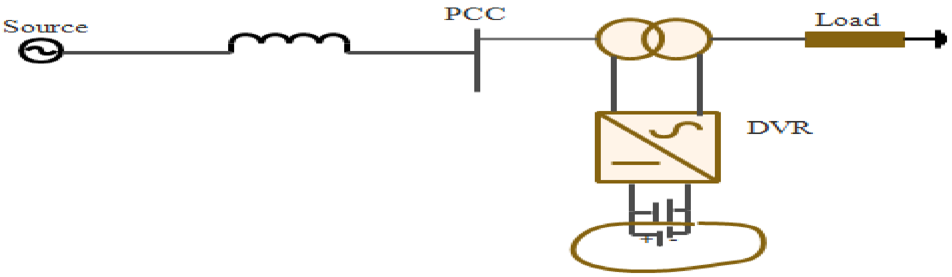


Figure 2-4: DVR connected to a distribution system**.**

2.2.1.4. Static Transfer Switch

Another way to protect a sensitive load from voltage dip is to use static transfer switches (STS). With a static transfer switch, a load can be fed from either the primary or secondary feeder. In the event of a voltage dip, the thyristor switches the device from the primary to the secondary feeder. The STS only protects distribution system equipment; if the transmission system has a voltage dip, both feeders of this device will be affected in [15]. Figure 2-5 shows the connection in a distribution network.

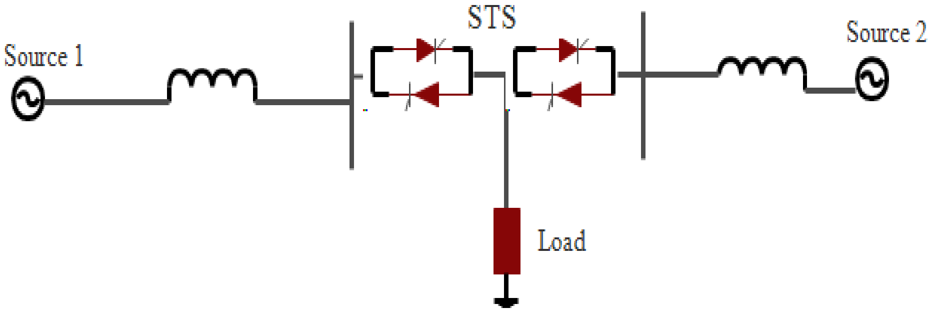


Figure 2-5: STS connected on a distribution system

2.2.1.5. Uninterrupted Power Supplies

Uninterrupted power supplies (UPS) come in a variety of configurations, but they all have one thing in common: their energy storage can supply active power. The capacity of the UPS energy storage to alleviate power interruption, voltage drop, and other power quality issues is determined by the size of the UPS energy storage. For critical low-power equipment, such as computers and servers, a UPS of roughly 5000 kVA can be used in [15]. Figure 2-6 depicts its relationship to the distribution system.

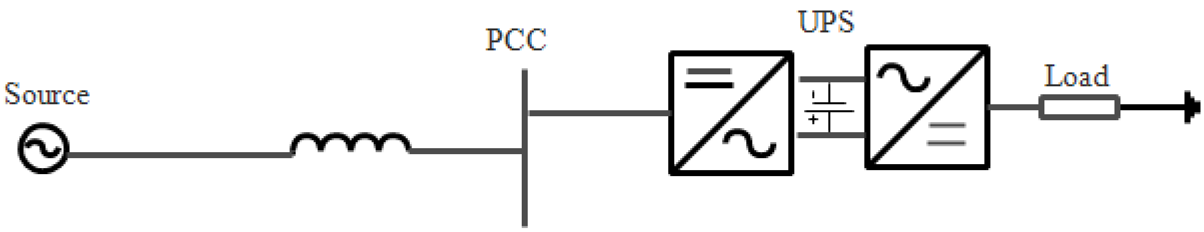


Figure 2-6: UPS connected on a distribution system.

2.2.2. Transmission Level

A high-voltage, direct current (HVDC) was the first power electronics technology to be used in a power network, with mercury ionic valves as the starting point. The HVDC is more commonly used in long-distance overhead and underground transmission networks as a power transmission alternative. It's also used to connect different frequency AC systems. FACTS devices increase the transmission capacity of transmission networks to their thermal capacity limit. When there are contingencies, FACTS makes it easier to manage voltage and stop the flow of loop currents, which causes excessive burden of transmission network resources in [16].

FACTS devices are also used to adjust for and improve an existing AC transmission system with a need to increase the system's power delivery capacity. It has been found that there is a significant growth in demand for electrical power, which is causing transmission system problems in [17].

2.2.2.1.Overview of Flexible Alternating Current Transmission Systems Devices

FACTS controllers are a type of power electronic controller that is very good at managing power flow on ac transmission lines. FACTS devices are a growing technology that can assist power utilities. FACTS technology applications, you can simply control load flow in the transmission network and bus voltage profile. The fundamental purpose of FACTS controllers is to increase the usable transmission system power capacity and to manage flow through transmission pathways the first and second generations of FACTS devices are separated into two groups based on technological features in [18].

In the initial generation of FACTS devices, a thyristor is used as the power semiconductor switching device, along with a massive reactor or capacitor banks, to absorb or inject reactive power from or into the transmission network. FACTS devices in the second generation use a GTO or IGBT as the power semiconductor switching device, together with tiny capacitors. The primary difference between the two generations of FACTS devices is their ability to exchange and generate real and reactive electricity in [19].

The controllers that use VSC as synchronous sources are the most advanced among the FACTS controllers. STATCOM controllers are of the VSC type, which are shunt connected, as are SSSC controllers, which are series connected, and UPFC controllers, which are both series and shunt connected.

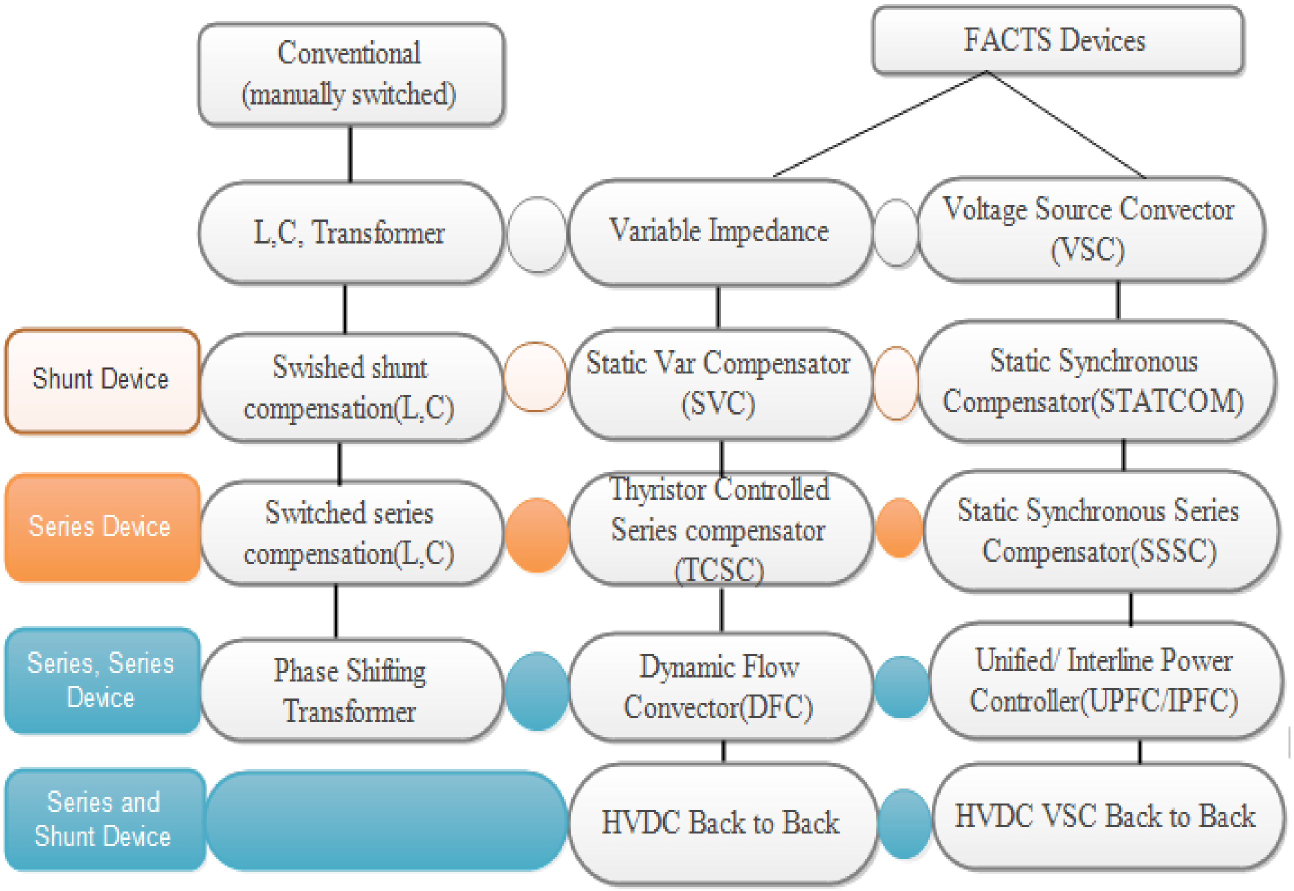


Figure 2-7: Over view of power flow controller devices

The following is how FACTS devices are used in [20]: -

- A boost in transmission capacity
- Power flow regulation
- Power quality improvement.

- Reactive power compensation
- Voltage stability margin improvement

FACTS controllers are categorized into four groups based on the arrangement to be placed in the transmission system in [21].

- Series Controllers
- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

Series Controllers: To meet the intended demand, the series controller could be a variable impedance device, such as a capacitor, reactor, or a power electronics-based variable source of main, sub-synchronous, and harmonic frequencies (or a combination). All series controllers, in theory, inject voltage in series with the line. An injected series voltage in the line is equal to the variable impedance multiplied by the current flowing through it. The series controller only delivers or consumes variable reactive power as long as the voltage is in phase quadrature with the line current. Any other phase relationship will entail dealing with real power. A typical line connection with a series impedance of $Z_{ij} = r_{ij} + jx_{ij}$.

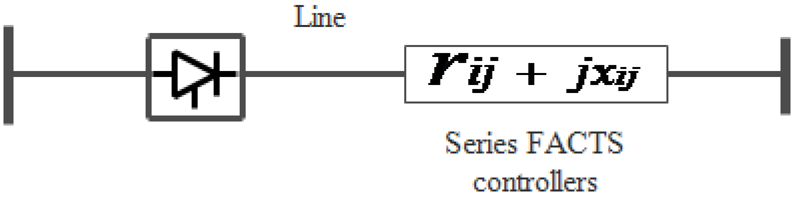


Figure 2-8: Series FACTS controller

Shunt Controllers: Shunt controllers can be variable impedance, variable source, or a mix of these, just as series controllers. Shunt controllers, in theory, inject current into the system at the point of connection. Because the changeable shunt impedance is connected to the line voltage, it creates a variable current flow, which indicates current injection into the line. The shunt controller only delivers or consumes variable reactive power as long as the injected current is in phase quadrature with the line voltage. Any other phase relationship will entail dealing with real power. Shunt controllers, like series controllers, can be variable impedance, variable sources, or a combination of the two, as shown in Figure 2-9.

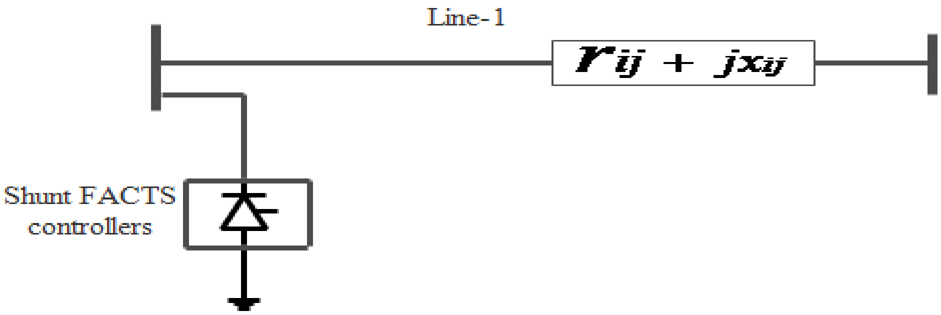


Figure 2-9: Shunt FACTS controller

Combined series-series Controllers: In a multiline transmission system, this could be a mix of independent series controllers that are operated in a coordinated manner. It might alternatively be a unified controller, where series controllers provide independent series reactive compensation for each line while also transferring real power between them via the power connection. The real power transfer capacity of the unified series-series controller, also known as the Interline Power Flow Controller, allows for the balance of both real and reactive power flow in the lines, maximizing the transmission system's utilization. The phrase "unified" here relates to the DC terminals of all controller converters being connected together for real power transfer, as seen in Figure 2-10.

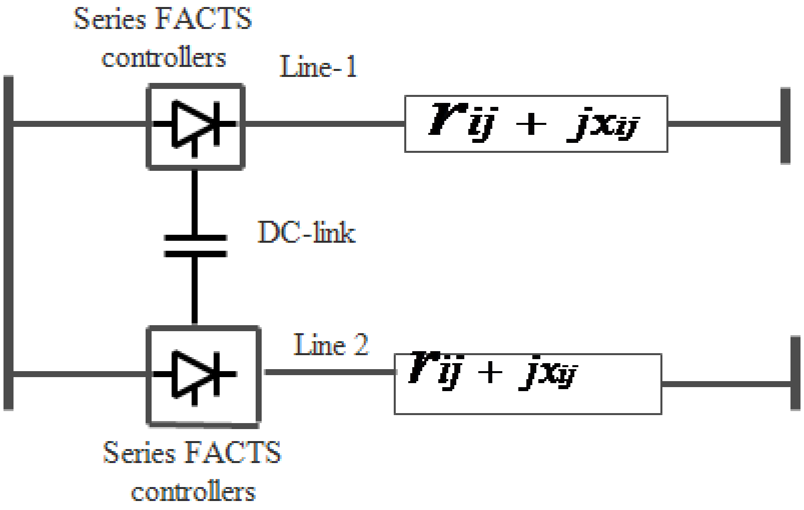


Figure 2-10: Combined series-series FACTS controller

Combined series-shunt Controllers: - This could be a Unified Power Flow Controller with series and shunt elements, or a combination of separate shunt and series controllers that are controlled in a coordinated manner. In theory, combined shunt and series controllers pump current into the system through the shunt part and voltage in series through the line through the series part. When the shunt and series controllers are unified, however, the power link allows for a true power exchange between the series and shunt controllers. When the shunt and series controllers are unified, a real power exchange between the series and shunt controllers can be accomplished via a DC link, as shown in Figure 2-11.

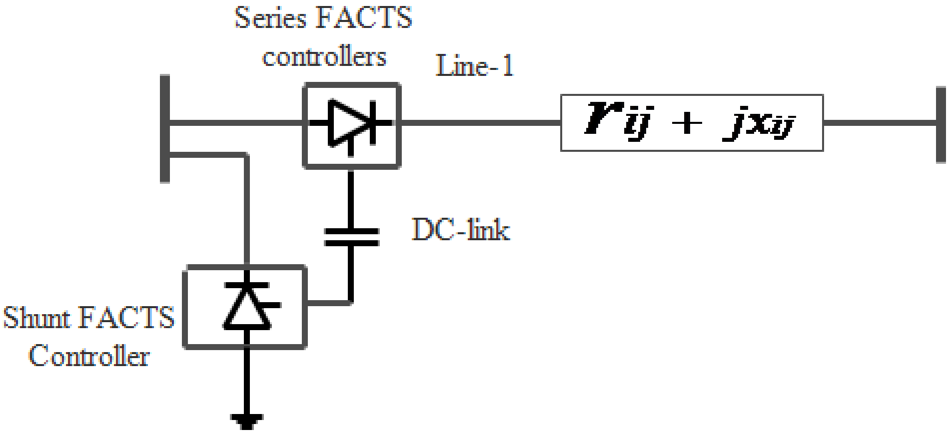


Figure 2-11: Combined series-shunt FACTS controller

FACTS controllers/devices are used in a variety of ways to improve the performance of power systems. Power flow balancing and control, Available Transfer Capability (ATC) improvement, loading margin improvement, congestion management, Reactive Power and Voltage Control are just a few of the steady state uses of FACTS controllers.

With the increasing capabilities of power electronic components, the development of FACTS-devices began. In voltage converters, devices for large power levels have been made accessible. The overall beginning points are network elements that influence reactive power and power system parameters. In this thesis, the SC, a member of the FACTS controller family, is used as a reactive power compensation device. It belongs to the Shunt Controllers category and serves as a quick generator or absorber of reactive power with the goal of maintaining or controlling particular electric power system parameters (typically bus voltage).

The FACTS controllers can also be categorized as follows, depending on the power electrical devices employed in the control: -

- Type of variable impedance
- VSC (Voltage Source Converter) based

Static Var Compensator (SVC) (shunt connected), Thyristor Controlled Series Capacitor or Compensator (TCSC) (series connected), and Thyristor Controlled Phase Shifting Transformer (TCPST) of Static and PST are examples of variable impedance type controllers (combined shunt and serial). S- Shunt Connected Static Synchronous Compensator (STATCOM), Series Connected Static Synchronous Compensator (SSSC), Interline Power Flow Controller (IPFC) (combined series-series), and Unified Power Flow Controller (UPFC) (combined shunt series).

VSC-based FACTS controllers provide advantages over variable impedance controllers.

2.3. Shunt Device and operational Principles

The injection of reactive power that the load requires is the primary operational principle of a shunt device. I_{SH} could be adjusted by modifying the current I in the line by varying the shunt controller impedance. The voltage drop in a transmission line is proportional to the current I in the line.

Shunt devices are used to change the receiving end-voltage value |vr| when the transmitting end voltage Vs. assumes a constant magnitude, as shown in Figure 2-12 in [22].

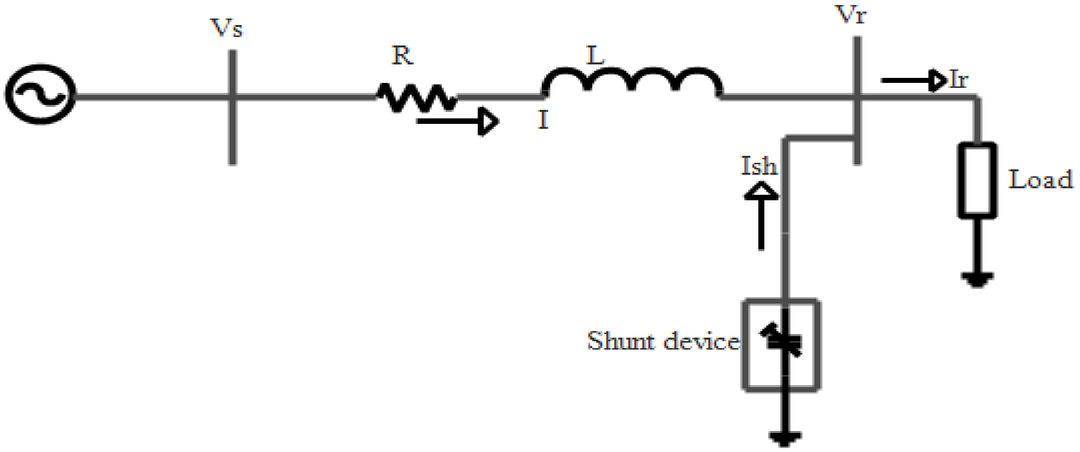


Figure 2-12: The operating principle of a shunt controller**.**

Equation (2-1) expresses this relationship as follows:

$V_r = V_s - IZ$

$V_r - (I_r - I_{sh})Z$

(2.1)

When the line is severely loaded, the current I_{sh} partially compensates for the load current I_r, lowering the line current I and resulting in minimal voltage-drop. The magnitude of the voltage is regulated by the shunt device by adjusting the impedance.

Shunt devices are classified as SVC devices, switched shunt-capacitor and inductor devices, and STATCOM devices. There are just two statuses in the switched shunt-capacitor and inductor controller (high and low). Its mode of operation and concepts are overly basic, preventing it from being widely adopted. Figure 2-13 depicts its configuration. The latter two shunt devices are detailed further below.

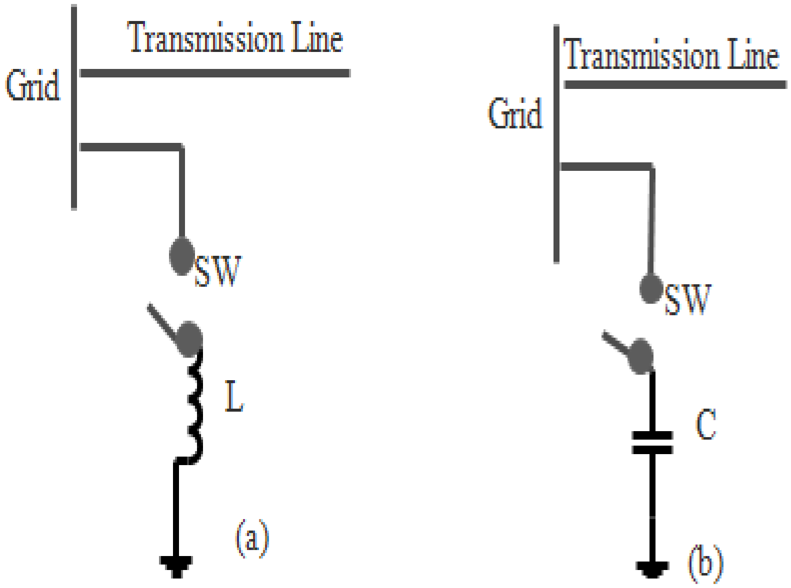


Figure 2-13: Switched-shunt capacitor and inductor configuration: (a) inductor; (b) capacitor

2.3.1. Static VAR Compensator

On high-voltage electrical transmission networks, this gadget creates fast-acting reactive power. SVC is mainly divided into two types:

- Thyristor Controlled Thyristor Switched Capacitor Thyristor Switched Capacitor Thyristor Switched Capacitor Thyristor Switched Capacitor (TS-TCR)
- Thyristor-Controlled Fixed Capacitance Reactor (FC-TCR)

Due to its versatility and the fact that it requires a smaller reactor with lower harmonics TSC-TCR is more widely used than FC-TCR. Figure 2-14 depicts a typical SVC connection in [23].

The TSC-TCR SVC type uses a series capacitor or inductor with an inverse-parallel thyristor. To quickly turn the capacitor on and off, TSC uses an inverse-parallel thyristor instead of mechanical connectors. A small series inductor limits inrush currents when severe transience occurs, such as when the capacitor begins to decay.

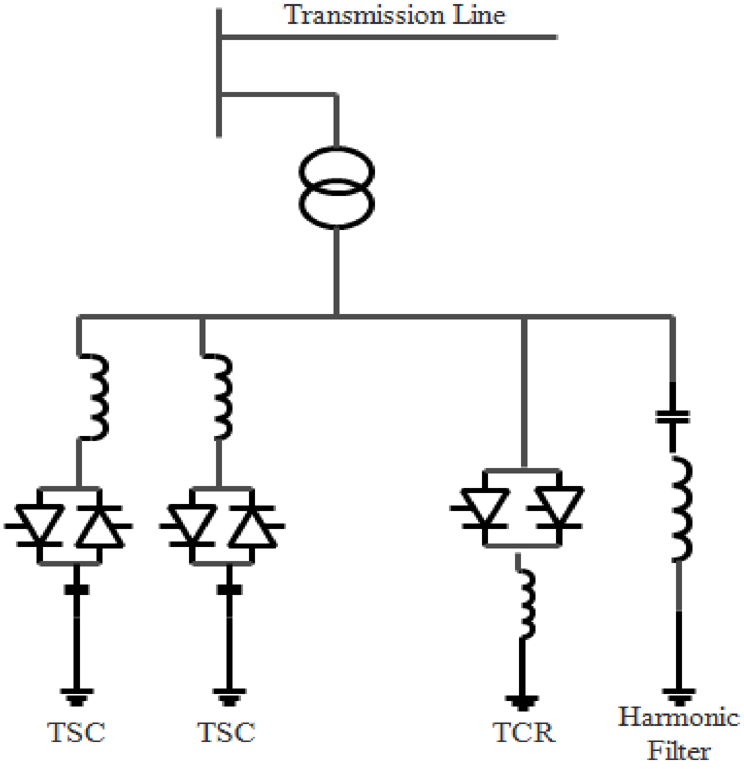


Figure 2-14: shows a typical SVC design.

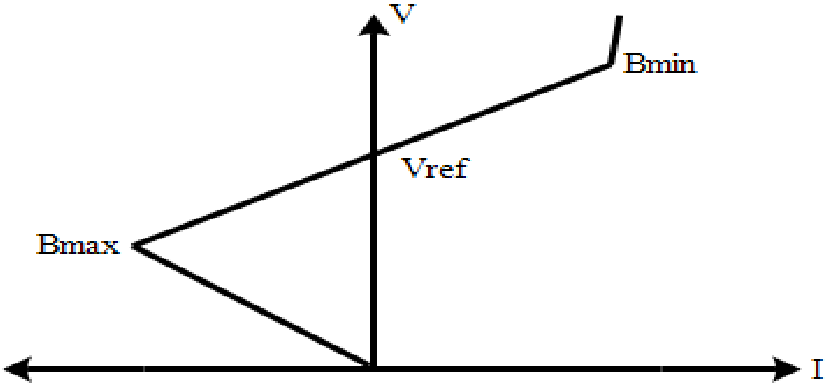


Figure 2-15: SVC terminal V-I characteristics**.**

In TCR, firing angle control is used to fire the thyristor and vary the current, allowing the shunt TCR reactance to be controlled. To ensure uninterrupted conduction, the firing angle is delayed by 90 to 180 milliseconds. SVC can behave as a controlled capacitor or inductor, injecting or consuming reactive power into the transmission bus as needed. It provides optimal performance on transmission lines when it is properly situated. The main disadvantages of SVC are that it is less effective for low bus voltage in terms of supplying sufficient reactive power. Second, SVC generates a large number of harmonics in the current, necessitating the use of a low cutoff frequency filter to decrease these harmonics in [24].

2.3.2. Static Synchronous Compensator

STATCOM is a VSC based on power electronics that can inject and absorb reactive power from the transmissions system. It consists of a DC capacitor, a VSC, and a coupling transformer. The STATCOM may inject leading or lagging quadrature ac current into the grid voltage, simulating capacitive or inductive impedance where it is attached in [25].

In Figure 2-16, a one-line diagram of the STATCOM controller, a magnetic coupling connects a transmission network bus to a VSC. The magnitude of the converter 3-phase output voltage, E, can be changed to regulate the reactive power exchange between the A.C. circuit as well as the converter. Current flows through the converter reactance and into the A.C. network when the output voltage exceeds the transmission network bus voltage, V. As a result, the converter injects reactive power into the A.C. system.

The flow of current from the A.C. will be caused by a decrease in the output voltage magnitude below the transmission network bus voltage. When the A.C. network voltage equals the converter output voltage, there is no reactive power exchange. STATCOM also performs the following tasks in [26]: -

- It has a small footprint; as compact electronic converters replace passive banks of circuit- elements;
- It has factory-built modularity, which reduces site work and commissioning time; and
- It uses encapsulated electronic converters, which has a small environmental effect.

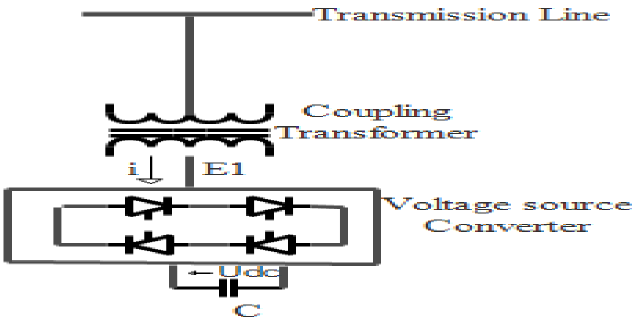


Figure 2-16: STATCOM configuration

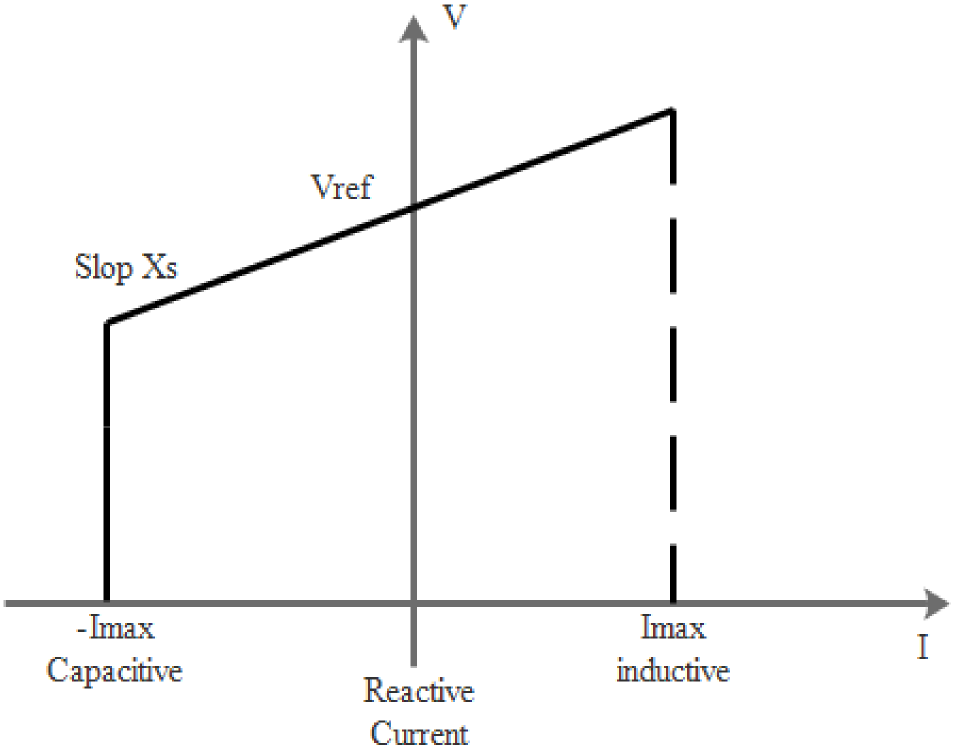


Figure 2-17: STATCOM terminal V-I characteristics

In order to incorporate STATCOM into load flow studies, the load flow algorithms must have suitable STATCOM modeling. The current injection model (CIM) and the power injection model (PIM) are two well-tested STATCOM models (PIM). In CIM, a current source is connected in parallel, but in PIM, a voltage source is connected in parallel behind an analogous reactance. The voltage can be adjusted using a network. When implemented into the transmission network, the reliability of the steady state STATCOM power injection model is very high and thoroughly established in [27].

2.4. Working Principle of STATCOM

To further understand how STATCOM works, we'll start by looking at the reactive power transfer equation. Have a look at these link two resources. V 1and V 2 are connected by impedance

Z = Ra + jX, as shown in figure 2-18.

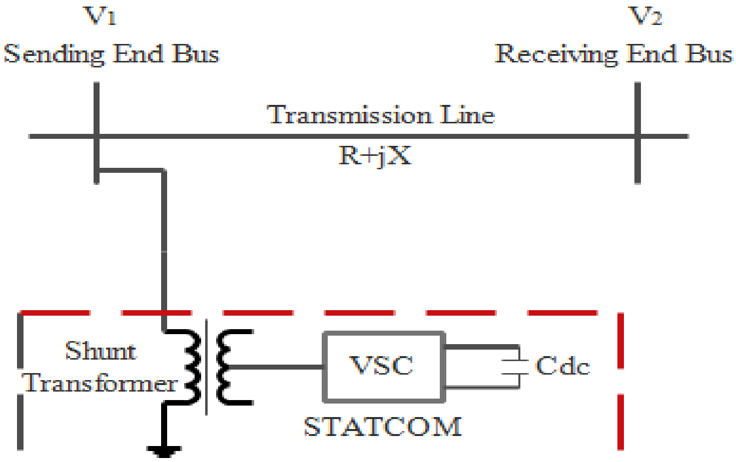


Figure 2-18: Working Principle of STATCOM

Assuming Ra=0,

The Reactive Power Flow Q is given as

$Q=(V_2/X)[V_1\text{Cos}\delta-V_2]$ (2.2)

In the above reactive power flow equation, angle δ is the angle between V1 and V2. Thus, if we maintain angle δ = 0 then Reactive power flow will become

Q = (V2/X) $[V_1-V_2]$ and active power flow will become

$P=V_1V_2\text{Sin}\delta/ X =0$ (2.3)

To conclude, if the angle between V_1 and V_2 is zero, the active power flow is zero, and the reactive

Power flow is determined by $(V_1 - V_2)$. As a result, there are two options for reactive power flow.

1) Reactive power will flow from source V_1 to V_2 if the magnitude of V_1 is greater thanV_2.

2) Reactive power will flow from source V2 to V1 if the magnitude of V2 is greater than V1. STATCOM uses this approach to manage reactive power.

The STATCOM is chosen for loss minimization and voltage stability margin augmentation of the A-BTS network in this thesis from among the many FACTS controllers explored thus far. The following are the primary reasons for selecting STATCOM: -

- It provides simultaneous or individual controls of basic transmission system parameters such as transmission voltage and phase angle.
- It has a unique capability to control real and reactive power flow and also regulate the bus voltage.
- It can perform the function of SVC.

2.4.1. Modeling of STATCOM

STATCOM has the following components:

- A Voltage Source Converter, VSC
- DC Capacitor
- Inductive Reactance
- Harmonic Filter

Voltage Source Converter, VSC: - The voltage-source converter transforms DC input voltage into AC output voltage. The following are two of the most prevalent VSC kinds.

Gate Turn-Off Thyristor Square-Wave Inverters: Because the basic component of the converter output voltage is proportional to the DC voltage, the output AC voltage is adjusted by adjusting the DC capacitor input voltage in this type of VSC.

DC Capacitor: - DC Capacitor is used to supply constant DC voltage to the voltage source converter, VSC.

Inductive Reactance: -A Transformer is connected between the output of VSC and Power System. Transformer basically acts as a coupling medium. In addition, Transformer neutralizes harmonics contained in the square waves produced by VSC.

Harmonic Filter: -Harmonic Filter attenuates the harmonics and other high frequency components due to the VSC.

STATCOM is a member of the FACTS shunt connected device family. Depending on the behavior of network voltage levels, STATCOM can efficiently manage network voltage by generating (capacitive) and absorbing (inductive) reactive power. Due to the STATCOM's strong dynamic performance and short-term responsiveness, this allows the operators to maintain the voltages at Point of Common Coupling (PCC) to the set point level by adjusting the magnitude and angle of the internal voltage. STATCOM’s structural schematic, equivalent representation and dynamic model are shown in Figure 2-19.

With active power exchange across the DC link as indicated in eq (2.4), the voltage Vsh is adjusted to set the local bus voltage and the power flow control using STATCOM as described in eq (2.4) ,(2.5). The analytical model of STATCOM's bus control expression is shown in eq (2.6).

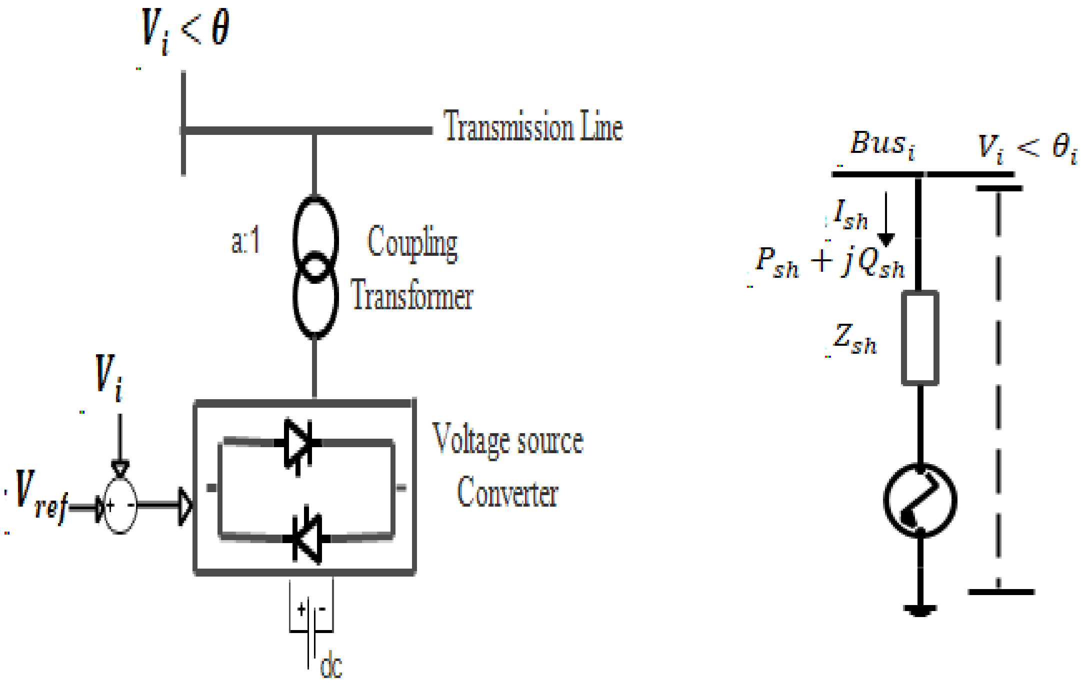


Figure 2-19: A simplified diagram equivalent electrical circuit of STATCOM

$$P_{sh} + jQ_{sh} = V_{sh} < \theta_{sh}(\frac{V_i < \theta_i - V_{sh} < \theta_{sh})^*}{Z_{sh}} \tag{2.4}$$

$$PE = Re(V_{sh} I_{sh}^*)=0 \tag{2.5}$$

$$V_i - V_{ref} = 0 \tag{2.6}$$

The complex voltages at the i^{th} bus and STATCOM terminal are represented by V_i and V_{sh}; the STATCOM apparent power is represented by Psh + jQsh; the shunt transformer impedance is represented by Zsh; and the bus voltage control reference is represented by Vref.

2.4.2. Dynamic STATCOM control strategies

A reliable power flow controller is needed for the optimization of electrical power transmission system capacity. Power flow controllers must be able to regulate electrical voltage and active and reactive power flow without jeopardizing the transmission system's stability and security.

The main objective of any compensation scheme is for it to respond quickly, be adaptable, and be simple to implement in [28]. The compensation objectives, dynamic, transient, and steady-state performance all benefit from STATCOM control. The STATCOM control technique is primarily based on a PI controller, which is used to limit the error and hence reduce the voltage derivation between the reference and actual observed values.

Different STATCOM control techniques are susceptible to non-ideal supply conditions and load change, necessitating careful controller design tuning for each individual insulator.

Furthermore, the cost of the system rises as a result of the usage of specialized equipment such as the LCL filter. The performance of the controller is dependent on the plant's characteristics and the values of the Kp and Ki parameters used in the PI controller in [28].

On the other hand, new suggested control techniques for STATCOM have been developed, such as an initially designed algorithm and a direct method that is based primarily on output voltage position and magnitude control.

To set the dynamic parameters of the optimal controller to achieve the optimal characteristics; steady state and dynamic, a unique AI approach based on ANN, FIS, ANFIS fused with a distinct algorithm system was utilized.

2.5. Artificial neural network

An Artificial Neural Network (ANN) is a data-processing standard based on how organic nervous systems, such as the brain, process data in [29]. The unique structure of the information processing system is a major component of this approach. It is made up of a large number of highly linked processing components (neurons) that work together to solve certain challenges.

ANNs, like people, learn by example. An ANN has configured for a Specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons.

An intelligent neuron's learning capacity is achieved by adjusting the weights in line with the chosen learning strategy. The majority of neural network applications fall into the following categories in [30].

- Prediction: to predict the output variables using input values
- Classification: to process the classification stage using input values
- Data Association: it is as classification, plus recognizing data that has errors
- Data conceptualization: process the inputs to group relationships can be figured out

The feature of the neural network is significantly a function of the interaction between the different neurons. The main architecture contains three neuron layers types they are Input layers' types, hidden layers' types and output layers' types.

The objective functions of optimization as well as depend on the data given about the transmission system which is in some cases needed to evaluate gain parameters and needed special control strategies as well as additional equipment, this led to the importance of using AI techniques for controlling STATCOM. This work will suggest using ANNs as a technique for tuning controller of STATCOM, which its controller constants is selected optimally using TLBO

2.6. Solution Methodologies for Optimal Power Flow

A large variety of algorithms for determining the best power flow have been described and implemented in power networks. Methods are divided into two categories: intelligent and conventional. Traditional methods' solution approaches have a number of flaws, necessitating the use of artificial intelligent algorithms in [31].

2.6.1. The Conventional Solution Methodologies

The deterministic approach optimization methods are often known as conventional or classical approaches. Gradient Method (GM), Dynamic Programming (DP), Linear Programming (LP), Quadratic Programming (QP), Newton Methods (NM), Lagrangian Relaxation Algorithm (LRA), Non-Linear Programming (NLP), Interior Point (IP) Methods, and Hessian Methods are examples of these techniques. Many of these traditional methods are used, particularly when the search space is non-linear in [32].

Despite the scholarly advances in classical techniques, the classical approach still has some limits in terms of implementation. The following are some of the restrictions that have been identified in [33]:-

- Poor convergence or Convergence issues.
- Computationally, the solution is rather expensive.
- Finding a single optimal solution and dealing with operational constraints are both difficult.

2.6.2. Intelligent Solution Methodologies

Intelligent methods, also known as Meta heuristic optimization methods, are artificial intelligence-based optimization methods. Examples are Genetic Algorithm (GA), Particle-Swarm Optimization (PSO), Artificial Bee Colony (ABC), Pattern Search (PS), Evolution Programming (EP), Firefly Algorithm (FA), Differential Evolution (DE), Harmony Search (HS), and Hopfield Neural Network (HNN), Gravitational Search Algorithm (GSA), and Tabu Search (TS) among others. Researchers had shown that these algorithms are endowed with in [34].

- Faster convergence rate or a higher rate of convergence.
- Ability to arrive at a worldwide solution in the shortest amount of time possible.
- Capabilities for dealing with complex systems that is efficient.

Table 2-3 presents a comparison of numerous intelligent approaches for addressing OPF problems, along with their strengths and weaknesses.

The goal of this study is to establish the best STATCOM placement and sizing for minimizing power losses and voltage stability margin enhancement on transmission lines. STATCOM is a VSC-based controller that supports the power system by supplying reactive power compensation and quick voltage control.

STATCOM increases transmission line capacity, improves voltage stability margin, angle stability, and dampens the system's oscillation pattern. STATCOM has piqued the interest of power researchers and operators in recent years as a means of assisting the system by supplying the appropriate reactive power and improving the voltage profile on transmission networks. STATCOM placement is an optimization challenge that necessitates lowering system loss and voltage stability margin enhancement while also meeting system constraints.

Table 2-1: Comparison of Meta-Heuristic Optimization Algorithms in [35-40**]**

Meta-heuristic Optimization Algorithm	Advantage	Disadvantage
Particle Swarm Optimization (PSO)	-The concept is simple and simple to implement. -The accuracy of parameter control is higher, and it consumes less memory. - It's easy to use with non-linear, discontinuous problems.	- Due to poor local/global searching capabilities, it is caught in local optima when dealing with strongly constraint problems. - It is simple to update without regard for the quality of the solutions.

Firefly Algorithm	-It not only involves the process of self-improvement with the current place, but it also encompasses. - The computation required to arrive at an optimal solution is quick. - It enhances its own environment.	- If the values are not carefully set, they may become locked in local optima. - The parameters are set. - There is no recall of past iterations that resulted in superior solutions.
Genetic Algorithm	- Because it works using coding of parameter sets, it can easily handle integer or discrete variables. - It does not employ derivatives or other auxiliary knowledge; it simply uses objective function information.	- It takes a long time. - It provides a lot of control options. - Being a stochastic algorithm, formally specifying convergence criterion is problematic.

Bacterial Foraging Optimization Algorithm	- Automatically adapt. - It converges at a global level, which prevents premature convergence. - Computation is quite quick. - Nonlinear functions are widely used, and more objective functions are handled.	- Because of its biased random walk, the swarming effect is inadequate for the ELD problem.
Artificial Bee Colony	- Only a few values are required. - It is widely used all around the world. - High degree of adaptability	- Time to compute is long.
Ant Colony Optimization	- It may be used to solve a wide range of optimization problems. - Ants can be employed in dynamic parallel applications since they move simultaneously and independently without supervision.	- Because theoretical analysis is difficult, research is conducted experimentally rather than theoretically. - Although convergence is guaranteed, it takes an unknown amount of time to attain. - Only applied to discrete-problems
Teaching Learning based Algorithm (TLBO)	-more accurate -Does not require any derivative -Follows the entire path to find its solutions	- it consumes lot of memory space. -It involves lot of iterations so is a time-consuming method.

Literature review

Researchers have proposed various ways for solving the problem of transmission line voltage profile improvement and power loss minimization in transmission systems. The most related works done by the researchers are presented below.

Based on evolutionary optimization techniques in [41] presented the optimal location for a unified power flow controller. The IEEE-14 bus case study was analyzed. In this case, the GA and PSO optimization methods were used in the system. Two evolutionary optimization techniques have been used in this work to find the best location for a UPFC to reduce active power losses in the power system, and the results are compared. Only one objective function, minimizing the active power loss of the power system, was considered for this purpose. This can be shown as follows:

$$minmize_F = \sum_{k=1}^{n} P_L \tag{2.7}$$

$$\mathrm{V_{min}} \leq \mathrm{V} \leq \mathrm{V_{max}}$$

$$\delta_{\mathrm{min}} \leq \delta \leq \delta_{\mathrm{max}}$$

$$\mathrm{Q_{min}} \leq \mathrm{Q} \leq \mathrm{Q_{max}}$$

In this case, the voltage magnitude, angle and size of FACTS device were pointed constraints and they were limited.

According to [42], artificial intelligence techniques were used to determine the best location for an SVC. A static var compensator was used in this study. The objective function for allocating this device is voltage deviation: -

$$minmize_F = \sum_{k=1}^{n} |1 - V_m| \tag{2.8}$$

$$0.95 \leq V \leq 1.1$$

$$Q_{min} \leq Q \leq Q_{max}$$

In this case, the voltage magnitude and size of the FACTS device were pointed constraints and they were limited.

According to [43] presented PSO-based location and parameter setting of advanced SVC controller in comparison to the genetic algorithm. In this part, the IEEE-14 bus case study is analyzed with only one objective function. The optimization problem mentioned here is to search for the optimal in comparison to the genetic algorithm in this paper presented PSO-based location and parameter setting of advanced SVC controller. The IEEE-14 bus case study is discussed in this part using only one objective function. Using the PSO and GA algorithms, the optimization problem presented here is to find the best position and set of FACTS parameters. The FACTS controller, it may be argued, is designed to reduce tiny signal oscillations in the power system after a disturbance, resulting in increased stability. This result in terms of minimization of the Critical Damping Index (CDI) is given by:

$$minimize_{CDI} = J = (1 - \tau_i) \tag{2.9}$$

The issue constraints are the limits on the FACTS devices' allowable placements and parameters. Both the PSO and the GA algorithms separately create the best set of parameters as well as the best location related to the FACTS device by minimizing the amount of objective function J. In this regard, PSO has been implemented for optimal parameter setting and identification of the optimal site for the FACTS device in a standard multi-machine power system to mitigate the small signal oscillation problem. The shortcoming of this method is that it may not give accurate results due to the risk of entrapment of solution into a local minimum.

According to [44], presented the optimal location of a UPFC based on the PSO algorithm bearing in mind the minimization of active power losses. In this part, the IEEE-14 bus study case is investigated. A UPFC was used in this study to compensate for the power. In this case, two objective functions are implemented as indices of the system performance

In this regard, objective functions can be illustrated follows;

$$U_1(x) = P_L \tag{2.10}$$

$$U_2(x) = \left|\frac{\Delta P}{\Delta Q}\right| + P_L \tag{2.11}$$

In this case, the voltage magnitude and angle and size of the FACTS device were pointed constraints and they were limited.

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

$$\delta_{min} \leq \delta \leq \delta_{max}$$

$$\mathrm{X_{Lmin}} \leq \mathrm{X_{FACTS}} \leq \mathrm{X_{Lmax}} \quad .$$

According to [45], a comparative analysis of reactive power optimization in a deregulated power system using various techniques is presented. The IEEE-30 bus study case will be discussed in this part. Real power is maximized in this scenario, while reactive power is minimized. Furthermore, sufficient reactive power should be provided locally in the system to keep the bus voltages within nominal ranges in order to meet the voltage ratings of customers' equipment. In this regard, the mathematical model of reactive power optimization and its algorithm was modified. In this case, FACTS devices are used to enhance the voltage profile. In this regard, PSO and the GA are used and the MATLAB program is deployed.

In this study, two objective functions are used: minimizing reactive power and voltage deviation. As usual there are a few constraints in the problem.

$$Q_i = -i\left\{V_i * \left[V_i Y_{ii} + \sum_{i=1}^{n} V_{ij}\, V_j\right]\right\} \tag{2.12}$$

$$V(i) = \sum_{i=1}^{n}(1 - V_i)$$

$$\mathrm{V_{min}} \leq \mathrm{V} \leq \mathrm{V_{max}}$$

$$\mathrm{Q_{min}} \leq \mathrm{Q} \leq \mathrm{Q_{max}}$$

$$\mathrm{T_{i-min}} \leq \mathrm{T_i} \leq \mathrm{T_{i-max}}$$

The use of the optimal genetic algorithm to optimize the voltage profile in power system networks using the SVC and UPFC was presented in [46]. The results were demonstrated using the IEEE-30 bus system. The voltage stability index was defined as follows in this case:

$$L_i = 1 - \sum_{i}^{g} V_j F_{ij} \;\; | \tag{2.13}$$

In this case, the system load-ability and voltage profile were improved and losses were reduced.

According to [47] presented the optimal location and parameter setting of multiple TCSCs for increasing power system load-ability based on the GA and PSO techniques. In this study, the IEEE-6 and IEEE-14 bus study case will be analyzed. In this case, one objective function has been defined. In this objective function there are two parameters. The first part is related to the cost of a FACTS device and the second part is the sum of two parts, which are thermal and bus voltage limit factors. The objective function can be defined as follows:

$$minimze_F = 1000 * C_{FACTS} * S * \lambda * VL \tag{2.14}$$

$$C_{FACTS} = 0.0015S^2 - 0.713S + 153.75 \tag{2.15}$$

$$\mathrm{V_{min}} \leq \mathrm{V} \leq \mathrm{V_{max}}$$

$$\mathrm{X_{Lmin}} \leq \mathrm{X_{FACTC}} \leq \mathrm{X_{Lmax}}$$

According to [48], a bacterial swarming algorithm for reactive power planning was used to find the best location for FACTS devices. The IEEE-30 and IEEE-118 bus study cases will be discussed in this part. The optimization's objective is to reduce real power losses while also enhancing the voltage profile.

$$f(x) = F_L + K_V F_V + K_Q F_Q \tag{2.16}$$

There are a few constraints:

$$\mathrm{V_{min}} \leq \mathrm{V} \leq \mathrm{V_{max}}$$

$$\mathrm{\delta_{min}} \leq \mathrm{\delta} \leq \mathrm{\delta_{max}}$$

$$\mathrm{Q_{min}} \leq \mathrm{Q} \leq \mathrm{Q_{max}}$$

$$\mathrm{X_{Lmin}} \leq \mathrm{X_{FACTC}} \leq \mathrm{X_{Lmax}}$$

$$\mathrm{T_{i-min}} \leq \mathrm{T_i} \leq \mathrm{T_{i-max}}$$

A hybrid particle swarm optimization approach for optimal positioning of an SVC device in power system planning is presented in [49]. This method was tested on the IEEE 68-Bus System.

In this study, one objective function is used that includes two parameters. The first part is related to the voltage profile at the bus-bar and the second part is related to the operation and installation cost. By replacing FACTS devices in the system, it can be seen that losses decreased.

$$F(x) = w_1 * V_K + w_2 * CO \tag{2.17}$$

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

$$Q_{min} \leq Q \leq Q_{max}$$

Presented evolutionary optimization strategies for optimal location and parameter setting of the TCSC in [50]. The IEEE-14 and IEEE-6 bus study cases were investigated in this research.

The main objective function in this case was stated in terms of the best location of FACTS to eliminate and reduce voltage variation in crucial situations. The following equations show the objective function and constraints:

$$minimize F_t \tag{2.18}$$

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

$$Q_{min} \leq Q \leq Q_{max}$$

$$\delta_{min} \leq \delta \leq \delta_{max}$$

$$-0.5X_L \leq X_{FACTC} \leq 0.5X_L$$

Simulation has been carried out on the IEEE-6 bus and IEEE-14 bus systems. The results achieved show that FACTS can improve sharply the security of a power system by minimizing the overloading of transmission lines and voltage deviation. Both algorithms found the same place to allocate the FACTS devices. The PSO algorithm is much faster than the GA technique and this is because in the GA there are features such as selection, mutation and crossover and the PSO does not have these features.

According to [51], an enhanced particle swarm optimizer for power systems was presented. The study case in this instance is a part of the Brazilian power network, which includes 45 bus-bars and ten machines. The PSO technique was used to optimize the case study, and the results were compared to those obtained using other techniques such as the BFA and GA. The results demonstrated that the PSO technique can find reasonable and optimal locations to allocate FACTS devices at a fast rate of convergence. In this case, there are two objective functions to be considered. The first is to minimize the voltage deviation and the second is to minimize the possible FACTS size. They can be defined as follows:

$$J_1 = \sqrt{\sum_1^n (V_K - 1)^2} \tag{2.19}$$

$$J_2 = 100,000 * \sum_1^M \eta p \tag{2.20}$$

$$J = w_1 * J_1 + W_2 * J_2 \tag{2.21}$$

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

$$0.95 \leq V_k \leq 1.05\,, K{:}\,1 \rightarrow N$$

$$Q_{min} \leq Q \leq Q_{max}$$

According to [52], the optimal location and parameter setup for a UPFC based on the GA and PSO to improve power system security under single contingencies has been proposed. The IEEE-6 and 14-bus systems were used in this research. The objective function that was used in this study is shown below: -

$$F_t = \sum_{L=1}^{nl} w_l \left(\frac{S_L}{S_L^{max}}\right) + \sum_{m=1}^{nb} w_m \left(\frac{V_m ref - V_m^{2n})}{V_{mref}}\right. \qquad (2.22)$$

Using a generic graphical user interface, [53] demonstrated the optimal placement of multiple types of FACTS devices to maximize power system load-ability. The IEEE-300 bus system was used as a case study in this research to demonstrate the simulation and validity of the findings. Objective function was defined as follows:

$$J = Max\{\lambda\} \qquad (2.23)$$

$$|\Delta Vb_i| \leq 0.05$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}$$

According to [54], particle swarm optimization was used to find the best location for the UPFC in electrical systems with line outages. The goal of this study is to improve the voltage profile and raise the system's load-ability. In this case, the IEEE-30 bus system was used to demonstrate the work's simulation and validity. The objective function is given below:

$$minimizeF = \pi_{line} Ov_{line} + \pi_{bus} vt_{bus} \qquad (2.24)$$

$$0.9 \leq v_b \leq 1.1$$

Research Gap

In this review, different case studies have been investigated and different types of objective function with constraints applied to the systems. All the algorithms have different characteristics and features in terms of fitness and convergence characteristics. Some of them are usually used in power systems and some of the techniques are rarely used in terms of optimization.

Therefore, in this study, the optimal placement of STATCOM to improve voltage profile, minimize the power loss and enhance power transfer capacity is identified and the teaching-learning based algorithm (TLBO) technique is used for the optimal sizing and location of the STATCOM device as optimization technique related results are compared with GA and PSO for the Alaba to Bukuluguma Transmission System network. The Objective function was defined as follows: -

$$minimize F1 = \min(P_L) \tag{2.25}$$

$$minimize F1 = \min(V_D) \tag{2.26}$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max}$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max}$$

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

$$\delta_{min} \leq \delta \leq \delta_{max}$$

Summary of reviewed works

Table 2.2 gives a summary of the reviewed works, the techniques used and the research gaps identified.

Table 2.2: Summery of the Reviewed works

Research work	Objectives	Technique/Method Used	Gaps
H. Shaheen et al [41]	The optimal size and location of UPFC must be determined in order to minimize active power losses in the power system.	Evolutionary optimization techniques using PSO and GA.	This works did not consider reactive power losses.

R. Sheeba et al [42]	In order to optimize the voltage profile, the optimal size and location of the SVC must be determined.	artificial intelligence techniques	The convergence speed was just a little slow.
D. Mondal at al [43]	The Critical Damping Index is reduced to enhance voltage stability by identifying the optimal size and location of SVCs.	Particle Swarm Optimization techniques (PSO)	Time to compute is long and the convergence speed was just a little slow.
A. Bhowmik et al [44]	To reduce active power loss, the optimal size and position of the SVC must be established.	Particle Swarm Optimization techniques (PSO)	Solution may get confined into local minimum.
R. Rekha et al [45]	Reactive power and voltage variation should be kept to a minimum.	Comparative analysis on reactive power optimization using PSO and GA.	The technique's values aren't as well-optimized.
S. J. Kumar et al [46]	Determination of the best location for SVCs and UPFCs in order to optimize the voltage profile in the system.	genetic algorithm (GA)	Time to compute is long.

G. Rashed et al [47]	To reduce costs, the optimal size and location of TCSCs must be determined.	genetic algorithm (GA) and particle swarm optimization (PSO)	Solution may get confined into a local minimum and the convergence speed was just a little slow.
Z. Lu et al [48]	Determination of the best size and position of various FACTS in order to minimize real power losses.	bacterial swarming algorithm (BSA)	This works is did not consider reactive power losses.
A. Mohammadi et al [49]	Determine the best size and position of the SVC to minimize overall power loss.	A hybrid particle swarm optimization approach	Solution may get confined into a local minimum
G. Rashed et al [50]	The appropriate size and position of the TCSC, as well as the reduction of voltage variation, must be established.	Genetic algorithm (GA) and Particle swarm Optimization (PSO)	The convergence speed was just a little slow
Y. Valle et al [51]	Minimize the voltage deviation and the size of the FACT.	Particle swarm Optimization (PSO)	Time to compute is long. .

H. I. Shaheen et al [52]	To optimize the voltage profile, the optimal size and position of the UPFC must be established.	Genetic algorithm (GA) and Particle swarm Optimization (PSO).	The convergence speed was just a little slow
E. Ghahremani et al [53]	Determination of the best location for the FACT device in order to maximize power system load-ability.	generic graphical user interface	Solution may get confined into local minimum.
J. S. Christa et al [54]	Determine the proper position for the UPFC in electrical systems with line outages to improve the voltage profile and maximize the system's load-ability.	Particle swarm Optimization (PSO)	The convergence speed was just a little slow
This work	Determine the best location for a STATCOM in order to improve voltage profiles and reduce power loss.	Teaching Learning Based (TLBO)	-real and reactive power loss was properly considered. - The results of the TLBO optimization technique are compared to those of GA and PSO.

CHAPTER THREE

3. METHODOLOGY

3.1. SYSTEM MODELING AND POWER FLOW

This thesis has four main objectives. It began with a Newton Raphson power flow analysis on the selected case study to identify transmission system problems. The TLBO-optimization technique is used to determine the location and size of STATCOM. The voltage stability index is used to determine the best location for the STATCOM device. The overall methodology of this thesis is depicted in Figure 3-1.

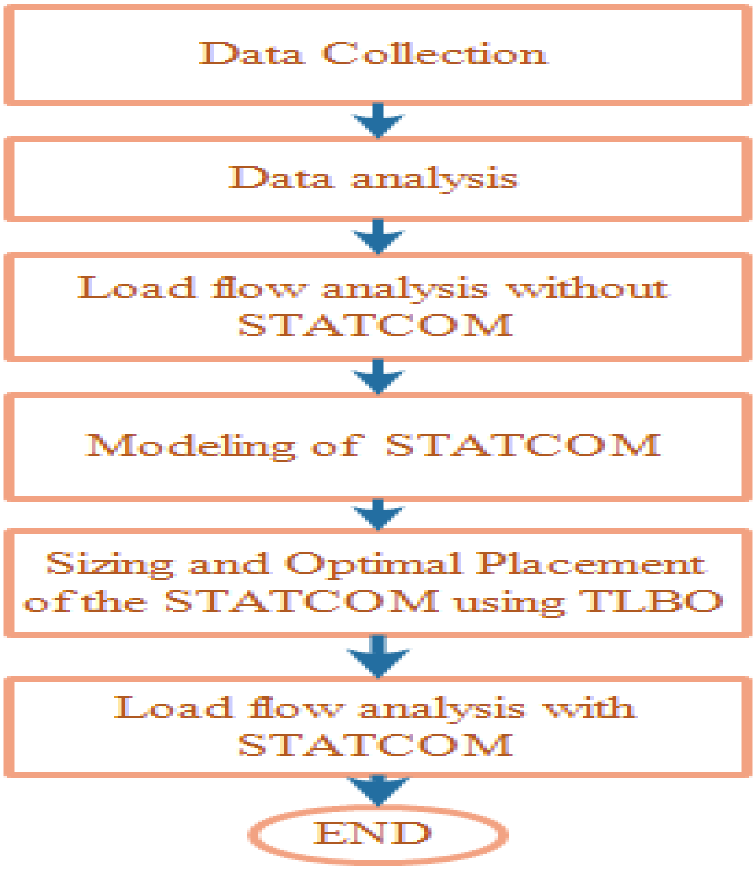


Figure 3-1: Flow chart of overall methodology of the thesis.

3.1.1. Data collection and analysis

The recent and necessary data for the transmission network is collected from the Alaba Substation through their recorded technical data regarding the transmission network.

The data collected includes: -

- The transmission line parameters.
- The peak load demand of the Alaba to Bukuluguma Transmission System network.
- The generation capacity of the power plants.

The collected data are analyzed and presented in Table 3.1 - Table 3.3

1. **Generation station**

Table 3-1: Generation Stations

NO	Generation Name	Pg (MW/unit)	Pmax (MW)	Pmin (MW)	Sn (MVA)	Qmax (Mvar)	Qmin (Mvar)	No. Generation units
1	Gilgel Gibe I	61	184	0	250	63	-63	3 units
2	Gilgel Gibe II	105	420	0	500	200	-200	3 units

2. **Load bus**

Table 3-2: Peak loads of the system at each sub-station.

Peak load at each Bus from EEU&EEP				
Bus no_	Name of Bus	MW Load peak	MW Load Min	MVAr Load
1	Alaba 132	10.22	2.12	4.21
2	Awassa II 132	30.2	7.8	14.6
3	Awassa I 132	23.4	5.8	9.6
4	Yirgalem II 132	28	9.5	21
5	Yirgalem I 132	10.9	3.1	4.25
6	Dilla 132	9.4	1.58	3.67
7	H/Mariam132	7.8	1.21	2.45
8	Bukuluguma 132	3.45	0.75	1.25

3. **Transmission line Parameters in Pu.**

Table 3-3: Transmission line data (EEU&EPP)

TL NO	From bus	To bus	R(pu)	X(pu)	B(pu)
1	Gilgl Gibe I 132	Alaba132	0.035481	0.070601	0.01383
2	Gilgel Gibe II 230	Alaba 230	0.092681	0.039867	0.1200611
3	Alaba 132	Hawassa II 132	0.019064	0.043245	0.3452754
4	Hawassa II 132	Hawassa I 132	0.031922	0.089447	0.2453741
5	Hawassa I 132	Y/alem II 132	0.025644	0.083875	0.4532172
6	Y/alem II 132	Y/alem I 132	0.013462	0.043211	0.5632121
7	Y/alem I 132	Dilla 132	0.023217	0.023152	0.5324133
8	Dilla 132	H/Mariam 132	0.023153	0.040017	0.2001306
9	H/Mariam 132	Bukuluguma 132	0.065122	0.031121	0.1123817

The Alaba to Bukuluguma Transmission System network single line diagram is drawn using EDRAW MAX software as shown in the figure below. The EDRAW MAX software is used in this thesis for only drawing purpose because it has a good feature to show all of the power system components. The power flow analysis is done by using MATLAB Simulation.

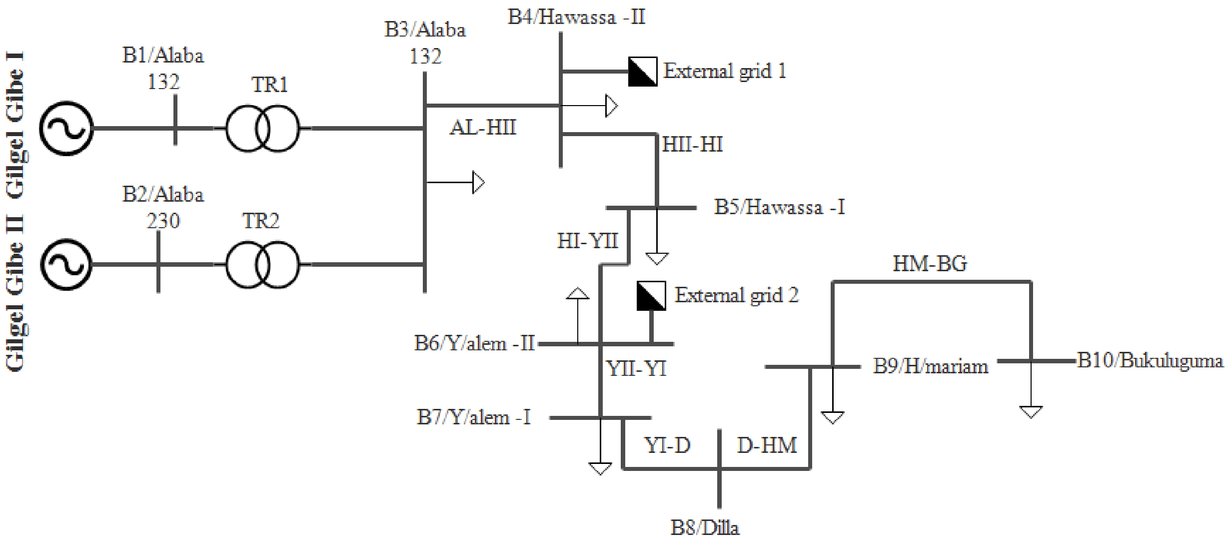


Figure 3-2: The Alaba to Bukuluguma Transmission System single line diagram

[Bus numbers are indicated by the letters: - B1, B2, B3, B4, B5, B6, B7, B8, B9, and B10].

External grids in Figure 3-2 show the remaining transmission network from the Yirgalem II sides and Hawassa II side. The parameters for the external grids are obtained from the actual EEP grid that was utilized to depict the power exchange between the case study system and the elements of the Ethiopian transmission system that were removed.

However, for the purposes of the research, this external grid network must be represented as an equivalent generator to reflect the influence of the external grid network on the component of the network for which studies are being conducted. The external grids are represented by generator buses in the MATLAB analysis in this thesis.

3.1.2. Transmission Line Modeling

Transmission lines are an important component of an electric power system. They enable transmission of electricity from the power plants to the consumers by carrying electric power from one end of the line (sending-end) to the other (receiving-end) in [55].

A line has four distributed electrical parameters affecting the way it transmits electric power from sending to receiving end; series resistance, series inductance, shunt capacitance, and shunt conductance. The distributed resistance and inductance form the series impedance of the line, while the capacitance and conductance present between conductors or conductor to neutral from the shunt admittance of the line. The value of these parameters depends on the cable material characteristics and on the electric and magnetic fields along and around the conductors. Therefore, the geometrical configuration of the lines also plays an important role in the determination of these parameters.

In order to study the line as part of the power system, it is important to be able to determine how line parameters influence the flow of power through the system. The line behavior in terms of wave propagation is of interest. Specifically, voltage and current relationships along the lines are needed. The model used to calculate voltage, current and power flow depends on the line length of the system.

For the purpose of performance analysis; transmission lines are classified into short, medium and long lines according to their length. Less than 80 km is short line, between 80 km and 250 km is medium line and more than 250 km is long line. The performance analysis varies from an approximate to detail depending on the line length. In this thesis, medium line model is used due to the area to be studied is 245 km length from the main generation station.

Let us make the following definitions of transmission line parameters to be used throughout this lesson and subsequent lessons;

r = line resistance per phase per unit length

L = line inductance per unit length

C = line capacitance per unit length

V_R = phase voltage at the receiving end.

I_R = receiving end current

V_S= phase voltage at the sending end

I_S = sending end current

3.1.3. Medium Line Model and it`s Representation

Capacitance of medium lines is significant and cannot be ignored; another element to be considered is the shunt conductance due to leakage current along insulators. This is referred to by simple G, and it is measured in Siemens. The total shunt admittance of a medium line is given by;

$$Y = (g + jwC)\, l \qquad (3.1)$$

However, for the purpose of this lesson, the *g* term is neglected then Equation (3.1) becomes;

$$Y = (jwC)\, l \qquad (3.2)$$

Where, l = line length

$\omega = 2\pi f$, where f is the frequency of the supply.

Figures 3-3 shows an equivalent circuit representation of a medium line. In this representation, half of the shunt admittance (capacitance) is lumped at each end of the line. The model is referred to as π model for obvious reasons.

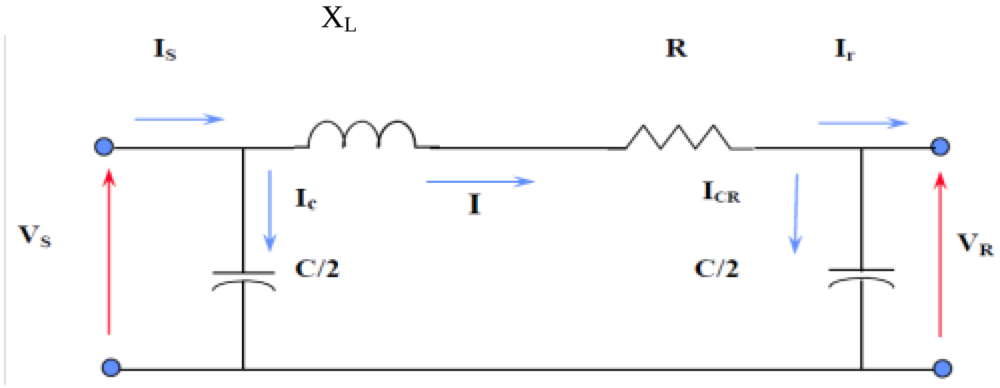


Figure 3-3: Nominal π Model representation of a medium length Transmission Line.

Where; $jX_L = j\omega L$

$C/2 = Y/2 = B/2$

Using KCL and KVL the following voltage and current relationships are derived.

$$I = I_R + I_{CR} \tag{3.3}$$

$$I = I_R + (Y/2)\, V_R \tag{3.4}$$

$$V_S = V_R + ZI \tag{3.5}$$

$$V_S = V_R\,(1 + ZY/2) + ZI_R \tag{3.6}$$

$$I_S = I + (Y/2)\, V_S \tag{3.7}$$

Substituting for I and V, equation (3.7) becomes;

$$I_S = Y\,(1 + ZY/4)\, V_R + (1 + ZY/2)\, I_R \tag{3.8}$$

The ABCD constants can be written as:

$$A = (1 + ZY/2)$$

$$B = Z$$

$$C = Y\,(1 + ZY/4)$$

$$D = (1 + ZY/2)$$

Equations (3.6) and (3.8) can be written as follows:

$$V_S = AV_R + BI_R \tag{3.9}$$

$$I_S = CV_R + DI_R \tag{3.10}$$

Transmission lines may be represented by a two-port network as shown in Figure 3-4.

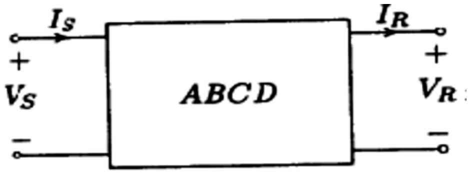


Figure 3-4: Transmission Line Two Port network representations**.**

Where, ABCD are Transmission Line complex constants.

3.1 .4. Transformer

The equivalent circuit for a transformer is shown in Figure 3-5. We can see from the figure that the currents I_i and I_j entering the two terminals and the voltages are V_i and V_j referred to the reference node in [56].

Assume that the transformer is lossless. The current entering at node (I_i) is calculated from;

$$I_i = -t * I_j \qquad (3.11)$$

The current I_j can be expressed by;

$$I_j = (V_J - tV_i)\ Y = -tYV_i + Y\ V_J \qquad (3.12)$$

Where, t is transformation ratio of the transformer.

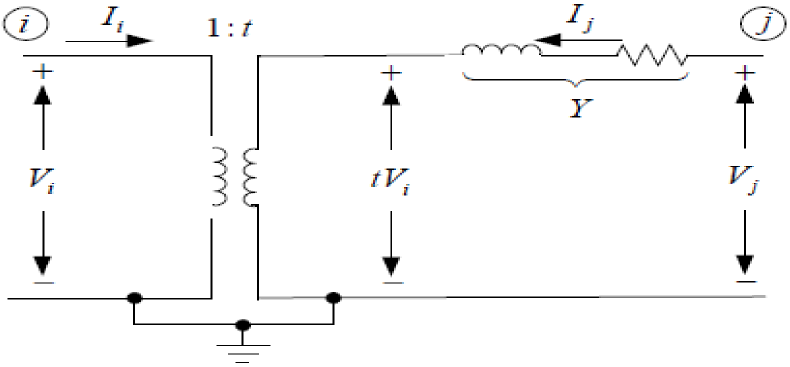


Figure 3-5: Reactance diagram for transformer

Multiplying by $-t^*$ and substituting I_i for $-t^*I_j$ yield;

$$I_i = tt * YV_i - Y\ V_J \qquad (3.13)$$

Setting $tt^* = |t|^2$ and rearranging (3.12) and (3.13) into *Y bus* matrix forms;

$$\begin{bmatrix} Y_{ii} & Y_{ij} \\ Y_{ji} & Y_{jj} \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \begin{bmatrix} t^2y & -t*y \\ -ty & y \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} = \begin{bmatrix} I_i \\ I_j \end{bmatrix} \qquad (3.14)$$

3.2. Power Flow Analysis

Power flow is very importance in system design, planning and expansion. With power flow analysis, the voltage values of all the buses in a network, under specified network condition of operation can be computed. Other quantities, such as current values, power values, and power losses, is easily calculated when the bus voltages are known.

This is needed for system planning and control. Power flow analysis is fundamental to power systems study. Several numerical solution methods are used to solve load flow equations. The Newton Raphson, Fast Decoupled, and Gauss-Seidel methods are the most common iterative methods in [57].

The N-R increases in quadratic progression, Gauss-Seidel method increases in arithmetic progression, while the Fast-decoupled increases in geometric progression. However, the most reliable and effective of the three power flow techniques is the Newton-Raphson due to its accurate and fast convergence in [58].

3.2.1. Classification of Buses

A bus is a node at which one or many lines, one or many loads and generators are connected. In a power system each node or bus in the system has four variables: voltage magnitude, voltage angle, real power and reactive power. During the operation of the power system, each bus has two known variables and two unknowns.

The main objective of the load flow is to find the voltage magnitude of each bus and its angle when the powers generated and loads are pre-specified. To facilitate this, we classify the different buses of the power system shown Figure3.11 in the chart below.

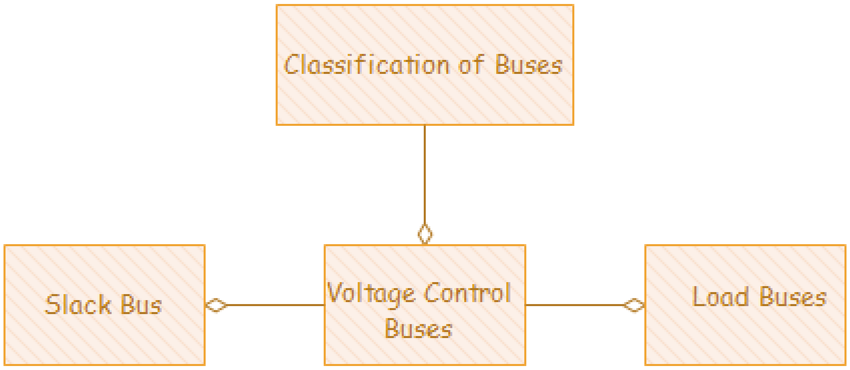


Figure 3-6: Classifications of Buses

Generally, the bus must be classified as one of the following bus types:

Slack Bus or Swing Bus or Reference Bus:

This bus is considered as the reference bus. Usually this bus is numbered 1(one) for the load flow studies. It must be connected to a generator of high rating relative to the other generators. Since it is the angle difference between two voltage sources that dictates the real and reactive power flow between them, the particular angle of the slack bus is not important. However, it sets the reference against which angles of all the other bus voltages are measured.

During the operation, the voltage of this bus is always specified and remains constant in magnitude and angle. In addition to the generation assigned to it according to economic operation, this bus is responsible for supplying the losses of the system.

As a consequence, the angle of this bus is typically chosen to be 0. Furthermore, it is assumed that the magnitude of this bus's voltage is known.

Generator Buses or Voltage Controlled Buses: -

These are the bus services that have generators attached to them. As a result, electricity production in such buses is controlled by a motive force, while terminal voltage is governed by power station stimulation. Keeping the input power constant through turbine-governor control and keeping the bus voltage constant using automatic voltage regulator, we can specify constant PGi and | Vi | for these buses. This is why such buses are also referred to as P-V buses.

It is to be noted that the reactive power supplied by the generator QGi depends on the system configuration and cannot be specified in advance. Furthermore, we have to find the unknown angle δi of the bus voltage.

Load Buses: In these buses no generators are connected so that neither its voltage nor its real power can be controlled. On the other hand, the load connected to this bus will change the active and reactive power at the bus in a random manner.

To solve the load flow problem, we have to assume the complex power value (real and reactive) at this bus. Hence the generated real power PGi and reactive power QGi are taken as zero.

The load drawn by these buses are defined by real power -PLi and reactive power -QLi in which the negative sign accommodates for the power flowing out of the bus.

This is why these buses are sometimes referred to as P-Q bus. The objective of the load flow is to find the bus voltage magnitude |Vi| and its angle δi.

The following table 3.4 summarizes the above discussion.

Table 3-4 summarizes types of bus

Bus type	Specified quantities	Unknown Quantities
Slack bus	|V|,δ	P, Q
Load bus	P, Q	|V|,δ
Controlled bus	P,|V|	Q,δ

3.2.2. Newton Raphson Load Flow

The technique starts with the initial guess of the unknown values follows by Taylor series expansion of the power balanced equations ignoring the higher order terms. Newton Raphson load flow method converges rapidly provided the initial are correctly guessed. However, a longer time is required to execute each iteration.

Expressing the current in terms of Y-bus gives in [59]:

$$I_i = \sum_j^n Y_{ij}\, V_j \qquad (3.15)$$

In polar form

$$I_i = \sum_j^n |Y_{ij}||V_j| \qquad (3.16)$$

At bus i, the complex power is expressed as:

$$P_i - jQ_i = V_i^* * I_i \qquad (3.17)$$

Substituting Equation (3-17) into Equation (3-18) gives,

$$P_i - jQ_i = V_i^* \sum_j^n |Y_{ij}||V_j| < \theta_{ij} + \delta_j \qquad (3.18)$$

By separation of Equation (3-19),

$$P_i = \sum_{k=1}^m [V_i|\,|Y_{ij}||V_j|\cos(\theta_{ij} + \delta_i - \delta_j)] \qquad (3.19)$$

$$Q_i = -\sum_{k=1}^m [V_i|\,|Y_{ij}||V_j|\sin(\theta_{ij} - \delta_i - \delta_j) \qquad (3.20)$$

Where,

I_i=current at bus i.

Y_{ij} =Mutual admittance between buses i and j.

Vi and Vj are calculated voltage of bus i and j.

θ_{ij} == phase angle at bus i and j.

P_i =Active and reactive power at bus i.

The non-linear algebraic equations (3.19) and (3.20) form a set.

The Jacobian Matrix

The Jacobian matrix generalizes the scalar-valued function gradient of many variables, which generalizes the derivative of a single-variable scalar-valued function in [60].

This means that for scalar-valued multivariate and single-variable functions, the Jacobian matrix is the gradient and derivative, respectively. The Jacobian can also be used to describe how much "stretching," "rotation," or "transforming" a transformation causes locally. The Jacobian matrix is the first-order partial derivative of a vector valued function in vector calculus. The linear Equation set is given by the Taylor series expansion of Equations (3-19) and (3-20) around the initial value, omitting terms of higher order:

$$\left[\begin{array}{ccccc|ccccc}
\frac{\partial p^{(k)}{}_2}{\partial \delta_2} & \cdot & \cdot & \cdot & \frac{\partial P^{(k)}{}_2}{\partial \delta_n} & |V_2|\frac{\partial P^{(k)}{}_2}{\partial |V_2|} & \cdot & \cdot & \cdot & |V_n|\frac{\partial P^{(K)}{}_2}{\partial |V_2|} \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & J_1 & \cdot & \cdot & \cdot & \cdot & J_2 & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
\frac{\partial P^{(k)}{}_n}{\partial \delta_2} & \cdot & \cdot & \cdot & \frac{\partial PP^{(k)}{}_n}{\partial \delta_n} & |V_2|\frac{\partial P^{(k)}{}_n}{\partial |V_2|} & \cdot & \cdot & \cdot & |V_n|\frac{\partial P^{(k)}{}_n}{\partial |V_n|} \\
\hline
\frac{\partial Q^{(k)}{}_2}{\partial \delta_2} & \cdot & \cdot & \cdot & \frac{\partial QQ^{(k)}{}_2}{\partial \delta_n} & |V_2|\frac{\partial Q^{(k)}{}_2}{\partial |V_2|} & \cdot & \cdot & \cdot & |V_n|\frac{\partial Q^{(k)}{}_n}{\partial |V_n|} \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & J_3 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & J_4 & \cdot & \cdot \\
\frac{\partial Q^{(k)}{}_n}{\partial \delta_n} & \cdot & \cdot & \cdot & \frac{\partial Q^{(k)}{}_n}{\partial \delta_n} & |V_2|\frac{\partial Q^{(k)}{}_n}{\partial |V_2|} & \cdot & \cdot & \cdot & |V_n|\frac{\partial Q^{(k)}{}_n}{\partial |V_n|}
\end{array}\right]
\begin{bmatrix} \Delta\delta^{(k)}{}_2 \\ \cdot \\ \cdot \\ \cdot \\ \frac{\Delta\delta^{(k)}{}_2}{\Delta|V^{(k)}{}_2|} \\ \cdot \\ \cdot \\ \cdot \\ \frac{\Delta|V^{(k)}{}_n|}{|V_2|} \end{bmatrix}
=
\begin{bmatrix} \Delta P^{(k)}{}_2 \\ \cdot \\ \cdot \\ \cdot \\ \frac{\Delta P^{(k)}{}_n}{\Delta Q^{(k)}{}_2} \\ \cdot \\ \cdot \\ \cdot \\ \Delta Q^{(k)}{}_n \end{bmatrix} \tag{3.21}$$

The linearized relationship between changes in voltage magnitude $V_i^{(k)}$ and angle $\delta_i^{(k)}$ and changes in real and reactive power $P_i^{(k)}$ and $Q_i^{(k)}$ is expressed by the Jacobian matrix equation. Partial derivatives are a type of partial derivative.

Equations (3-19) and (3-20) evaluate at$\delta_i^{(k)}$, and the Jacobian matrix elements are given by $\Delta V_n^{(k)}$. Equation (3-16) [10] gives the expression in compact form.

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}=\begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \frac{\Delta|V|}{|V|}\end{bmatrix} \tag{3.22}$$

Where

ΔP and ΔQ = power residuals

J = Jacobian matrix

$$\begin{bmatrix}\frac{\partial p}{\partial\delta} & \frac{\partial p}{\partial|V_i}\\ \frac{\partial Q}{\partial\delta} & \frac{\partial Q}{\partial\delta}\end{bmatrix} \tag{3.23}$$

The voltage-control buses' voltage values are specified. The Gaussian-elimination method is used to eliminate ‘m' ΔV and ΔQ equations and the related columns in the Jacobian matrix if there are ‘m' voltage-controlled buses in the transmission network. The procedure of Gaussian elimination is conducted on the associated coefficients matrix.

As a consequence, there are n – 1 real power constraints and n – 1 – m reactive power constraints, with a Jacobian matrix of order (2n – 2 – m).

J_1 The diagonal and the off-diagonal of J1 are

$$\frac{\partial p_i}{\partial\delta_i}=\sum_{j\#1}^{n}|V_i\Big|\Big|V_j\Big|\Big|Y_{ij}|\sin(\theta_{ij}-\delta_i-\delta_j) \tag{3.24}$$

$$\frac{\partial p_i}{\partial\delta_i}=-|V_i\Big|\Big|V_j\Big|\Big|Y_{ij}|\sin(\theta_{ij}-\delta_i-\delta_j)\ \text{j\#1} \tag*{(3-25)}$$

The diagonal and off-diagonal elements of J2 are

$$\frac{\partial p_i}{\partial|V_i|}=2|V_i|Y_{ij}|cos\theta_{ii}+\sum_{j\#1}^{n}|V_i\Big|\Big|V_j\Big|\Big|Y_{ij}|(\theta_{ij}-\delta_i-\delta_j) \tag{3.26}$$

$$\frac{\partial p_i}{\partial|V_j|}=-|V_i||Y_{ij}|\cos(\theta_{ij}-\theta_i-\theta_j)\ \text{j\#1} \tag{3.27}$$

The diagonal and off-diagonal elements of J3 are

$$\frac{\partial p_i}{\partial\delta_i}=\sum_{j\#1}^{n}|V_i\Big|\Big|V_j\Big|\Big|Y_{ij}|\cos(\theta_{ij}-\delta_i-\delta_j) \tag{3.28}$$

The diagonal and off-diagonal elements of J4 are

$$\frac{\partial p_i}{\partial V_j}=-|V_i||Y_{ij}|\cos(\theta_{ij}-\delta_i-\delta_j)\ \ \text{j\#1} \tag{3.29}$$

The power mismatch is expressed as:

$$\Delta P_i^{(k)}=P_i^{sch}-P_i^{(k)} \tag{3.30}$$

$$\Delta Q_i^{(k)}=Q_i^{sch}-Q_i^{(k)} \tag{3.31}$$

The estimated values of voltage magnitudes and angle are:

$$\Delta P_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{3.32}$$

$$|V_i^{(k+1)}| = V_i^{(k)} + \Delta|V_i^{(k)}| \tag{3.33}$$

Where, $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ = difference in calculated and scheduled values.

P_i^{sch} and $Q_i^{sch}$are scheduled real and reactive power at bus i.

$P_i^{(k)}$ and $Q_i^{(k)}$ = calculated real and reactive power at bus i.

$\delta_i^{(k)}$ = calculated angle.

$\Delta\delta_i^{(k)}$ = change in calculated angle.

$|Vi\ (k$+1) | = the different between voltage value at bus i.

$|Vi\ (k)$ | = most recently voltage bus value. K and (k+1) denote previous and next iteration respectively.

3.2.3. Power Flow Algorithm of Newton-Raphson

The Newton-Raphson load flow solution process is described in this part, and the flowchart is shown in Figure 3-7.

- The voltage magnitudes and angles for load buses are set to 1.0 and 0.0, respectively.
- Equations (3-19) and (3-20) calculate Pi and Qi for load buses are computed using Equations (3.30) and (3.31).
- Pi and ΔPi are computed for voltage controlled-buses using Equations (3.19) and (3.35).
- Calculate the elements of the Jacobian matrix (J_1 , J_2 , J_3 , and J_4).
- Triangular factorization and Gaussian elimination methods are used to solve simultaneous Equation (3.19).
- The updated voltage values and angles are calculated using Equations (3.32) and (3.33).
- The process continues till the $\Delta P_i^{(k)}$and $\Delta Q_i^{(k)}$are smaller than the tolerance.

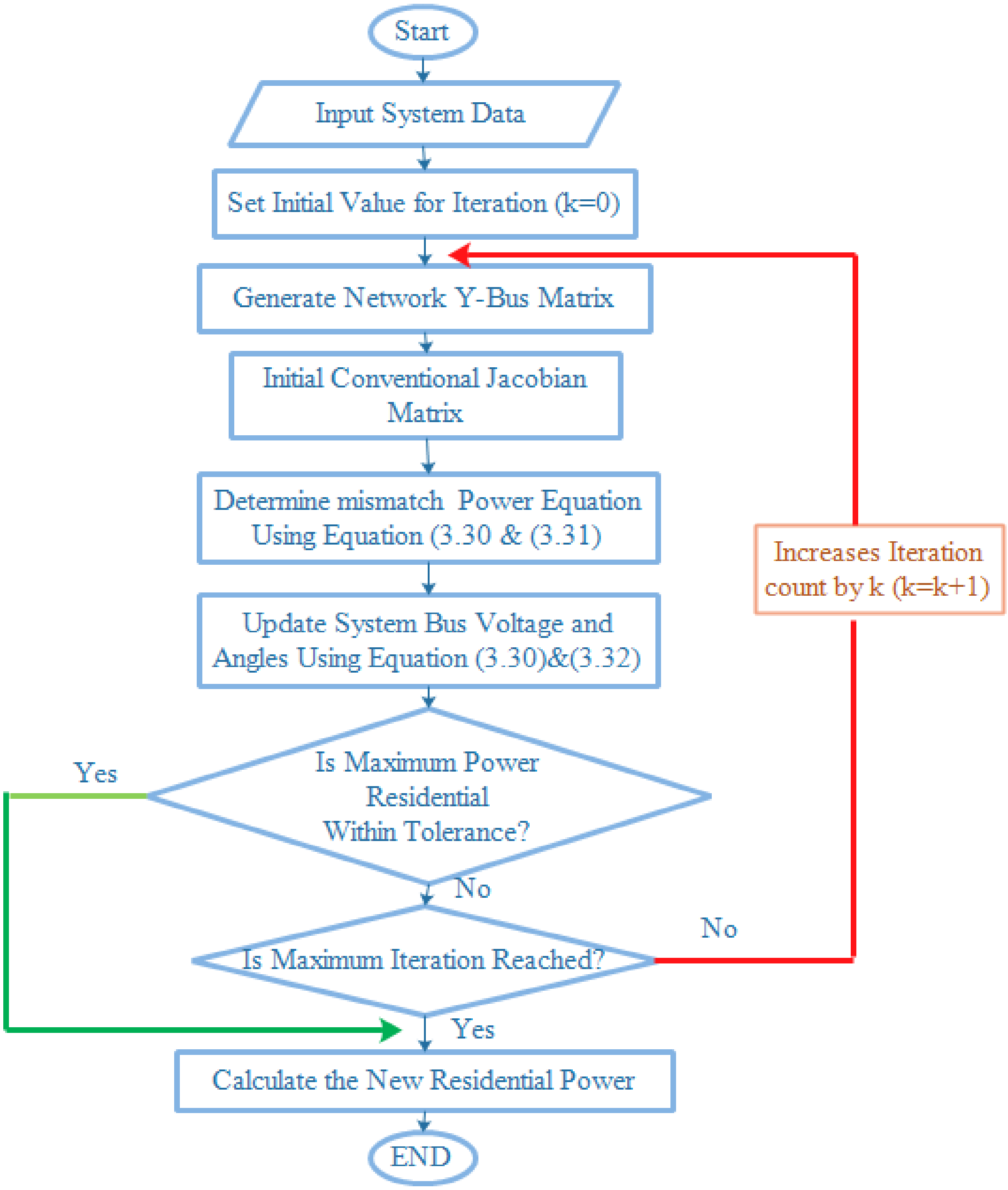


Figure 3-7: Algorithm for Newton Raphson Power flow Solution

3.3. Power Losses

Technical and non-technical losses are both present in electrical power transmission networks. Technical losses are connected to energy transmission processes that occur due to the physical characteristics of power system equipment and architecture, such as copper loss in conductor cables, transformer switches, and generators in [61]. The nontechnical losses come from the customer management process, which includes improper meter operation and unlawful usage in coordination with emergency responders.

3.3.1.Power loss calculation

Consider two buses associated by a branch as a part in a transmission system displayed in Figure 3.10, where buses k and k+1 are the sending and receiving end buses, correspondingly. As mentioned in Fig.3.10, the real power (k,k+1) and reactive power Q(k,k+1) flowing between buses k and k+1 can be derived by applying the formulae given below:

pk, k+1= pk+1,,+$PLoss$(k,k+1) (3.34)

Qk, k+1=Qk+1,,+$QLoss$(k,k+1) (3.35)

Where pk+1,eff, and Qk+1,eff, are the total effective real and reactive power supplied beyond the bus k+1 respectively, $PLoss$(k,k+1) and $QLoss$(k,k+1) are the active and reactive power losses between buses k and k+1 respectively.

The line losses can be calculated in the transmission system in lines in [62]. The real and reactive power loss in the line section between buses k and k+1 from equation (3.34) and (3.35) can be determined as:

$$P_{loss}(k, k+1) = I_{K,k+1}^{2} * R_{K,K+1} \qquad (3.36)$$

$$P_{loss(K,K+1)} = \left(\frac{P_{K,K+1}^{2}}{|V_{K+1|^{2}}}\right) * R_{K,K+1} \qquad (3.37)$$

$$Q_{loss}(k, k+1) = I_{K,k+1}^{2} * X_{K,K+1} \qquad (3.38)$$

$$Q_{loss(K,K+1)} = \left(\frac{Q_{K,K+1}^{2}}{|V_{K+1|^{2}}}\right) * X_{K,K+1} \qquad (3.39)$$

The total real power loss (P_{TL}) and reactive power loss (Q_{TL}) of the TS can be calculated by the addition of losses in all line sections, which is given by:

$$P_{TL} \ = \sum_{K=1}^{Nb} P_{loss(k,k+1)} \qquad (3.40)$$

$$Q_{TL} = \sum_{K=1}^{Nb} Q_{loss(k,k+1)} \qquad (3.41)$$

Where, Nb is a total number of branches.

3.4. Voltage Drop Calculation

All equipment connected to the distribution system is designed to be used in a certain definite voltage as per [62]. It is not practical, to serve every customer on a power transmission at the same voltage corresponding exactly to the name plate voltage because the voltage drops exist in each part of the power system from generating to the customer's meter. The voltage deviation function is expressed by:

$$\Delta \boldsymbol{V} = \sqrt{3} \times \sum_{i=1}^{Nb} I_i \left(R_i cos\theta + X_i sin\theta\right) L_i \tag{3.42}$$

Where,

I_i : $Current\ at\ bus\ i$

R_i : $Conductive\ resistance\ at\ bus\ i$

x_i : $Conductor\ inductive\ reactance\ at\ bus\ i$

L_i : $Length\ of\ circuit\ at\ bus\ i$

θ_i : $Phase\ angle\ of\ load\ at\ bus\ i$

3.5. STATCOM modeling and configuration on Transmission Network

A STATCOM can be used as a variable amplitude and phase angle synchronize voltage source. As a result, it has the capacity to regulate the voltage on its bus.

The STATCOM is a regulating power utility that is linked to the transmission system in shunt mode and is one of the FACTS devices. A STATCOM may be used as a variable magnitude and phase angle synchronous voltage source. As a result, it is capable of adjusting the voltage on its bus. For STATCOM modeling, two modeling approaches are used: average modeling and detailed modeling. Uses mathematical models of voltage converters for many electrical connections in a serial or parallel network. STATCOM is a shunt-connected VSC device that absorbs or injects active and reactive current through PCC (see fig 3-8) [63].

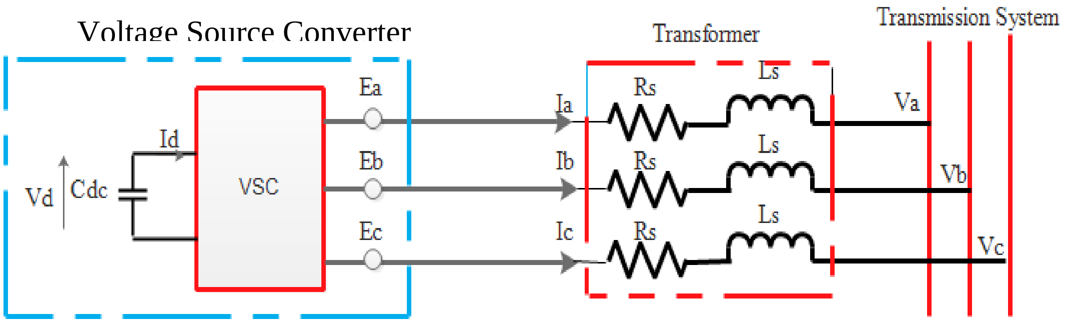


Figure 3-8: Equivalent model of STATCOM

$R_s and L_s$: STATCOM transformer resistance and inductance respectively

Eabc: are the phase voltages on the AC side of the converter.

Vabc: are the ac system side phase voltages.

iabc: are phase currents.

Id: is capacitor current.

Cdc: is dc capacitor value.

According to the system design shown in Figure3-8, the three phase load voltages coordinates may be expressed as in Eq. (3.43) [64].

$$\begin{bmatrix} V_{la} \\ V_{lb} \\ V_{lc} \end{bmatrix} = R_l \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} + L_i \frac{d}{dt} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \qquad (3.43)$$

Then, as in Eq. (3.43), may be translated into a revolving reference frame (3.44) [64]

$$\begin{bmatrix} V_{ld} \\ V_{lq} \end{bmatrix} = R_l \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + L_l \frac{d}{dt} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + L_l \begin{bmatrix} 0 & -w \\ w & 0 \end{bmatrix} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} \qquad (3.44)$$

3.5.1. VSC AC-side Model

Eqs. (3.45) and (3.46) may be used to calculate the source voltage V s and the converter output voltage [64].

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \frac{a_1}{L_1} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{b_1}{L_1} \frac{d}{dt} \begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{c_1}{L_1} \begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{d_1}{L_1} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3.45)$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \frac{a_2}{L_1} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{b_2}{L_1} \frac{d}{dt} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{c_2}{L_1} \begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{2}{L_1} \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} \qquad (3.46)$$

Where,

$a_1 = (R_s L_1 - R_l R_s)$

$b_1 = -(L_s L_f + L_s L_l + L_l L_f)$

$C_1 = -(R_f L_s + R_l L_s + R_f L_l)$

$d_1 = (L_s + L_l)$

$a_2 = -(R_s L_f + R_l L_f + R_s L_l)$

$b_2 = -(L_s L_f + L_f L_l + L_l L_s)$

$C_2 = (R_f L_1 - R_l L_f)$

$d_2 = (L_f + L_l)$

3.5.2. VSC DC-Side Model Equations

Eq (3.47) [64] gives the power balancing equation for VSC.

$$V_{dc} I_{dc} = \frac{3}{2}\left(e_d i_{ed} + e_q i_{eq}\right) \tag{3.47}$$

Vdc may be calculated using the current balancing formula Eq (3.48) [65]

$$\frac{d}{dt} V_{dc} = -\left(\frac{V_{dc}}{R_{dc} C_{dc}} + \frac{i_{dc}}{C_{dc}}\right) \tag{3.48}$$

.

3.5.2. DC bus capacitor design

The Cdc may be calculated using the theory of energy conservation as Current compensation requires a sufficient DC connection voltage, which may be computed using Eq. (3.49) [65]:

$$\frac{1}{2} C_{dc} [V_{dc}^2 - V_{dc1}^2] = 3KAVlt \tag{3.49}$$

Vdc: is reference DC bus voltage

$Cdc1$: is minimum level of the DC bus voltage

V: is phase voltage

I: is the phase current

t: is the time for which the DC bus voltage is to be recovered

K: factor for variation of energy during dynamics a: is the over loading factor.

3.5.3. DC bus voltage design

Current compensation requires a sufficient DC connection voltage, which may be computed as [65]:

$$V_{dcmin} > \sqrt{2V_{L-L(r.ms)}} = \sqrt{2}\sqrt{3}V_{L-N(r.ms)} \tag{3.50}$$

3.6. Proposed methodology

In terms of transmission network optimization, the study satisfied the requirements. More than one minimization objective will be examined, each based on a different optimization technique and assumptions.

Matlab simulation of the network's first condition power model, and the term "optimize the system" refers to a stable operating condition that does not violate any system security or stability constraints. This is done by evaluating the limits and stability constraints of teaching and learning-based solutions.

The second condition was that the researcher used TLBO with the new best method and controlled STATCOM by AI technique to determine the best optimal STATCOM size and location.

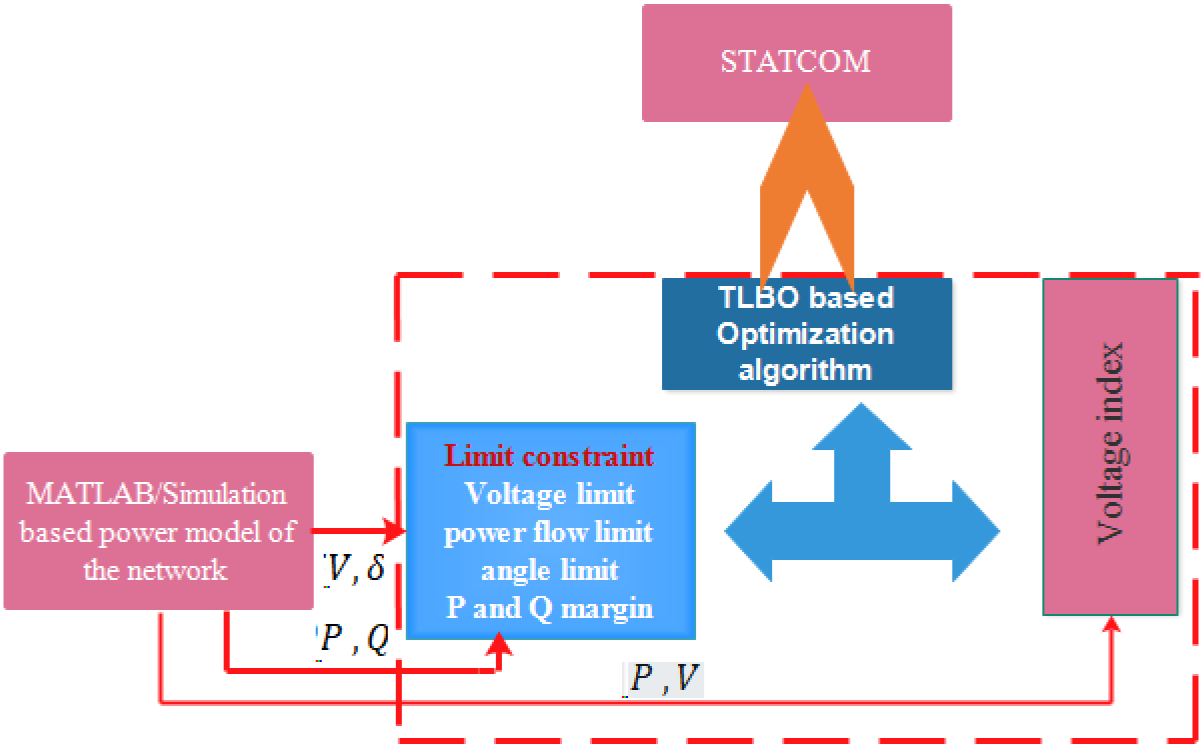


Figure 3-9: Proposed method controller block schematic

Problem Formulation

The objective is to find the appropriate STATCOM controller location and size to reduce the active and reactive losses and consequently improves the system voltage profile.

The objective function is the sum of line losses as shown in Equation (3.51):

Minimized F_1= power loss (P_{Tloss})

$$\boldsymbol{P_{Tloss} = \sum_{t=1}^{N_{branch}} |I_{Bt}|^2 * RZ_t} \tag{3.51}$$

Minimize F_2 =Minimizing Voltage deviation

$$\boldsymbol{V_D = \sum_{t=1}^{N_{Bus}} (V_t - V_t^{ref})^2} \tag{3.52}$$

Constraints

The problem is subjected to the following constraints:

Equality constraints

The equality constraints are load flow equations expressed as: -

$$P_{Gi} - P_{Di-} \sum_{j=1}^{NB} V_i \, V_{ij} V_{ij} \cos\left(\delta_i - \gamma_i - \gamma_j\right) = 0 \tag{3.53}$$

$$Q_{Gi} - Q_{Di-} \sum_{j=1}^{NB} V_i \, V_{ij} V_{ij} \sin\left(\delta_i - \gamma_i - \gamma_j\right) = 0 \tag{3.54}$$

Inequality Constraints

The inequality constraints on real power flow;

$$P_{Gi}^{min} \leq PGi \leq P_{Gi}^{max}$$

$$Q_{Gi}^{min} \leq QGi \leq Q_{Gi}^{max}$$

$$V_{i}^{min} \leq Vi \leq V_{i}^{max}$$

$$\delta_{i}^{min} \leq \delta i \leq \delta_{i}^{max}$$

Reactive power generation limit (Size) of STATCOM

$$Q_{STC}^{min} \leq Q_{STC} \leq Q_{STC}^{max} \; ; \quad i \in N_{STC}$$

The line flow limit expressed as a transmission loading constraint (P_{ij}) is given as

$$P_{ij} \leq P_{ij}^{max}$$

Where,

NL = the number of transmission line.

VSM = the voltage Stability margin.

V_{ij} = the voltage at the buses i and j of K^{th} lines.

G_{ij}= the conductance at the buses i and j of kth line.

V_{STC}^{min} and $V_{STC}^{max}$are the STATCOM’s minimum and maximum voltages, respectively.

P_D = the power demand.

P_L = the total power loss.

P_{Gi} = the power generated at bus i.

Q_{Di} = the reactive power demand at bus i.

Q_{Gi} = the reactive power compensator at bus i.

S_i = the sending end apparent power

3.6.1. Implementation of TLBO and voltage stability index

The voltage at each bus in a power system should be within acceptable limits, as should the line flows. These constraints are necessary to ensure that integrating STATCOM into the system does not raise the cost of voltage control or line replacement. The Voltage Stability Margin Improvement Index penalizes the size-location pair that results in larger voltage deviations from the base voltage [66]. In addition to reactive power compensation, the optimal position of compensating devices increases load-ability decreases power loss and improves voltage stability margin and power quality. In this article, a novel Voltage index (VI) is used to assess which bus has the best possibility of having a STATCOM installed. Lower VI and lower bus voltage levels have a higher possibility of being identified as proper STATCOM placement in the TS [67]. The estimate of these optimal buses is largely utilized to meaningfully reduce the search space for the optimization method [67]. TLBO is used to determine the ideal STATCOM size for the best buses.

3.6.2. Optimal Location of STATCOM based on Voltage Stability Index

To limit the solution space to a few buses, voltage sensitive nodes are first identified by penetrating STATCOM with the total system loading capacity at each node at a time, and then the voltage stability index (VSI) is calculated using equation (3.55). The STATCOM is located at the node with the lowest VSI.

The Bus Voltage Improvement Index (VPII) is defined as Eq (3.56)

$$VSI(k+1) = |V_K|^4 - 4[P_{K+1} * X_K - Q_{K+1} * R_t]^2 - 4[P_{K+1} * R_K - Q_{K+1} * X_K]|V_t|^2$$

(3.55)

$$VSI = \frac{1}{\lambda + max_{i=2}^{n}(|1 - V(STATCOM)|} \tag{3.56}$$

Where;

VSI is the voltage value after STATCOM installation.

λ: Is a scalar value

3.6.3. Optimal size of STATCOM

The procedures below are done to find the optimal size of STATCOM [68].

- The STATCOM is first installed at the node with the lowest VSI.

- The size of STATCOM is varied in continuous steps from a minimal value to a value equal to system loading capacity while keeping the output power constant until the smallest system losses are discovered.
- The STATCOM size that results in the least amount of losses is considered optimal.

3.7. Real Power Loss Reduction Index

The objective of STATCOM size and placement is to reduce the power system's system power loss. When a STATCOM is deployed at a bus, the Actual Power Loss Reduction Factor Index per node is defined as the ratio of percentage reduction in real power loss from a base scenario.

The Real Power Loss Reduction Index (PLRI) is calculated as follows:

$$PLRI = \frac{P_L(base) - P_L(STATCOM)}{P_L(base)} \qquad (3.57)$$

Where, $(base)$: is active power loss before STATCOM installation.

PL $(STATCOMi)$: is the real power loss in study system after installation of STATCOM.

3.8. Reactive Power Loss Reduction Index

The Reactive Power Loss Reduction Factor Index has been included in the objective function to determine the influence of STATCOM on reactive power losses. When an STATCOM is put on a bus, this refers to the percentage reduction in reactive power loss compared to a base scenario.

Reactive Power Loss Reduction Index (QLRI) has expressed as;

$$QLRI = \frac{Q_L(base) - Q_L(STATCOM)}{Q_L(base)} \qquad (3.58)$$

$(base)$: The reactive power loss before STATCOM installation.

Ql $(STATCOMi)$: The reactive power loss in study system after installation of STATCOM

3.9. Proposed artificial neural network controller for the system

The controllers' primary function in STATCOM is to detect voltage violations in the system while reducing errors.

3.9.1. Dynamic Controller of STATCOM

The shunt converter regulates both the AC and DC bus voltages at the terminals. It uses two voltage regulation loops, one for controlling AC and DC voltages and the other for regulating both.

The control system includes:

- A phase-locked loop (PLL) that handles the three-phase AC voltage's positive-sequence point.
- The d-axis and q-axis points of the AC three-phase voltage and currents were calculated using the PLL's output.
- Measuring devices for the d-axis and q-axis components of AC positive-sequence currents and voltages to be controlled, such as the DC voltage Vdc.

An AC and DC voltage regulator is used in an external regulation loop. A current regulator is used in an internal current regulation loop.

The voltage supplied by the PWM converter is controlled by this regulator. The control of the series branch in a STATCOM contains two tiers of functions, one for active power and the other for reactive power. We will try to fine-tune the settings of the power PI regulator's integral and proportional gains (Ki and KP) to get the best dynamic response.

To modify the settings of the PI controller's parameters, we will first apply the traditional technique mentioned in the preceding section. Then we will use Artificial Intelligence approaches to achieve the best tuning of the PI controller parameter values; this provides all of the benefits and uses all of the AI concept's alternatives, and the controlling process will get the essential adaptability, flexibility, and intelligence.

An ANN is used to control STATCOM in this study by evaluating gain parameters based on distribution bus voltage level.

3.9.2. Topology of the ANN

In data mining, an ANN is a common statistical learning technique. The organic neural network of the human brain inspired the main idea of ANN. The human brain is made up of a huge number of neurons that are linked together in a complicated structure. The structure of ANN is similar to that of the human brain; it anticipates events by learning information and storing it within the neurons by varying connections and weights in [69].

ANN could be a good solution for many complex problems that are difficult to tackle using traditional mathematical and computer methods. As a consequence, for tweaking STATCOM controller gains, this study used a common sort of neural network model known as feed forward. Figure 3-10 depicts the basic design of an ANN feed forward in [70]. Each node (neurons) in one layer is connected to each node in the following layer in the ANN's three-layer architecture: input nodes, hidden nodes, and output nodes.

The number of nodes in the input layer corresponds to the number of input features in the training dataset, whereas the number of nodes in the output layer corresponds to the number of outputs. In the middle layer, the number of hidden nodes is usually somewhere between those two figures. Because both over fitting and under fitting have an impact on training results, the number of hidden nodes is critical.

The training strategy for the ANN is based on altering the weights Wij and biases Bj in [71]. The error function is specified as Eq (3.59) in [71]

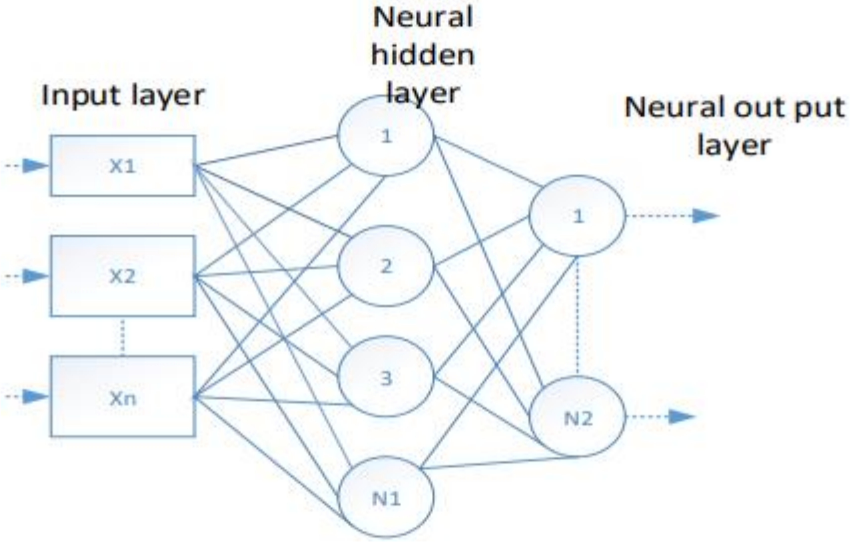


Figure 3-10: Architectural model of artificial neural network

$$\mathrm{J} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{e(i)}^2 \qquad (3.59)$$

The number of output neurons is N, and the instantaneous error between the actual and estimated output value is e(i). Because the hidden layer has no target values, the Wij optimization technique is repeated until the error is minimized and assigns the value yj to the jth neuron in the hidden layer, which is defined in terms of the input values xi in [71].

$$Y_i = \tanh\left(\sum_{i=1}^{n} W_{ij}X_i + b_j\right) \qquad (3.60)$$

The activation function is the nonlinear activation function. For the activation function, which was supposed to replicate the neuron receiving input signals from its neighbors, other functions might be utilized. If the hidden layer grows larger, Eq. (3.60) will be used to calculate the values of the next layer of hidden neurons from the values of the present layer. A linear combination of the neurons in the layer directly before the output layer can calculate the output neurons zk, as shown in Eq (3.61) in [71]

$$Z_k = \sum_{J} W_{ij}Y_j + b_k \qquad (3.61)$$

The STACOM (Vac regulator, Vdc regulator, current regulator, and PLL regulator) controller gains are determined using the ANN algorithm. The algorithm parameters are chosen according to Eq (3.62). The objective function is minimization of root mean square error (RMSE) between the actual measured voltage and reference voltage (1pu). Eq. (3.62) provides the RMSE and the objective function.

$$RMSE=\sqrt{\boldsymbol{\frac{1}{n}\sum_{i=1}^{n}(v_1 - v_{ref})^2}} \qquad (3.62)$$

Where,

RMSE: Root mean square error.

Vi: Actual voltage.

Vref: Reference voltage (1pu).

n: Number of samples

Various constraint conditions on which ANN is optimizing

1. This network has been designed to select the value of Vac (kp) and Vac (ki).

$$K_{P\_ac}^{min} \leq k_{p\_ac} \leq K_{P\_ac}^{max}$$

The values of PI regulators of STATCOM (Vac (kp) is kept in the range [0.001–10]

$$K_{i\_ac}^{min} \leq k_{i\_ac} \leq K_{i\_ac}^{max}$$

The values of PI regulators of STATCOM (Vac (ki) is kept in the range [0.001–3500]

2. This network has been designed to select the value of Vdc (kp) and Vdc (ki)

$$K_{P\_dc}^{min} \leq k_{p\_dc} \leq K_{P\_dc}^{max}$$

The values of PI regulators of STATCOM Vdc (kp) is kept in the range [0.0001–10]

$$K_{i\_dc}^{min} \leq k_{i\_dc} \leq K_{i\_dc}^{max}$$

The values of PI regulators of STATCOM Vdc (ki) is kept in the range [0.01 – 20]

3. This network has been designed to select the value of ir(kp) and ir(ki)

$$K_{P\_ir}^{min} \leq k_{p\_ir} \leq K_{P\_ir}^{max}$$

The values of PI regulators of STATCOM ir(kp) is kept in the range [1–10]

$$K_{i\_ir}^{min} \leq k_{i\_ir} \leq K_{i\_ir}^{max}$$

The values of PI regulators of STATCOM ir(ki) is kept in the range [0.001–1500]

4. This network has been designed to select the value of PLL(kp) and PLL(kp)

$$K_{P\_PLL}^{min} \leq k_{p_{PLL}} \leq K_{P_{PLL}}^{max}$$

The values of PI regulators of STATCOM PLL(kp) is kept in the range [5–100]

$$K_{i\_PLL}^{min} \leq k_{i\_PLL} \leq K_{i\_PLL}^{max}$$

The values of PI regulators of STATCOM PLL(ki) is kept in the range [5–3000]

3.10. Optimization Techniques

Up to now, many intelligent search techniques have been proposed and developed to solve the optimization problems that are complex problems instead of using traditional methods due to their accuracy and robustness. In this paper, three different algorithms explained below used to solve the optimal placement of STATCOM problem considering different objectives.

3.10.1. Teaching Learning Based Optimization (TLBO)

Teaching Learning Based Optimization (TLBO) is population-based optimization algorithms for the interaction between teachers and students in the class. The teaching learning-based optimization algorithm is the teaching and learning process that encouraged algorithms based on the teacher output of learners in the class. Teaching Learning Based Optimization algorithm is a teaching and a learning process but, a teacher is the consequence of learners in the class.

The algorithm defines two basic methods of the learning:

- The teacher (known as teacher phase)
- The interaction with the other learners (known as learner phase).

Initialization to be able to define population X, there is a random method concerned in the first step. The boundaries within the search method must be involved with in a matrix of N×D.N is the number of students in the class which is similar to population size. On the other ways, D the number of the courses being offered and G is the iteration process.

The initial random of the i and j rank of the matrix is being calculated in the below equation.

$$x_{(ij)}^{1}=x_{j}^{min}+rand\times(x_{j}^{max}-x_{j}^{min}) \qquad (3.63)$$

Where: rand = a variable between 0 and 1 to show random uniform distribution within that range.

x_j^{min}=minimum value of j^{th}parameter.

x_j^{max}= maximum value of j^{th}parameter.

j= 1, 2, 3 … D , i= 1, 2, 3… N and g= 1, 2, 3… G

The student parameter with would be ith parameter at iteration G is formulated in the below equation.

$$x_{(i)}^{g}=[x_{(i,1),}^{g}x_{(i,2)\,K}^{g}\ ,\ x_{(i,j),K}^{g}\ ,x_{(i,D)}^{g}] \qquad (3.64)$$

The TLBO is classified into two parts Teacher phase and Learner phase action of both phases is clarified below

Teacher Part

In the teacher's part, there is a vector called M^{g} which is the mean value of the students in the class for each topic that would be calculated at iteration G. the below equation represents M^{g}it is a more effective way represented as equation.

$$M^{g}=[m_{1,}^{g} \quad m_{2,}^{g} \quad ,K, \quad m_{j}^{g} \quad ,K,m_{D}^{g}]$$

For each iteration the teacher selected best minimum objective this algorithm carries on with replacing the students' mean values that approach the teachers' values. To be able to get an improved student course, the algorithm forms a differential vector of the existing mean values, which all have weights that are randomly calculated. The vector gets additional to the current population of students. The below equation represents the new student vector.

$$x_{(new)}^{g}=x_{(i)}^{g}+rand\times(X_{Teacher}^{g} - \ T_{F}\ M^{g}) \tag{3.65}$$

Where: r_2 = a random number between 0 and 1.

$\mathrm{T}_{\mathrm{F(teacher\ factor)}}$ = A value that is either 1 or 2 that randomly with change in each iteration.

T_{F} = round [1+r_2] (To select T_{F} randomly with the same probability between 1 and 2)

Note that, T_{F} is not considered a parameter that teaching learning-based optimization uses. It is a randomly selected value and will not require it as an input.

Learner Part

As it was described before student technically will learn from each other rather than their teacher. Each student interacts with the other student and in this method will learn more. The students are randomly interacting with the other students and start the knowledge transfer. It is the second part of the algorithm where learners rise their knowledge by interacting between themselves. The learner interacts randomly with other learners for rise his or her knowledge.

The learner learns new things if the other learner has more knowledge than him or her. The below equation mathematically represent the student learning interaction, calculation of $\mathrm{x}_{\mathrm{new(i)}}^{\mathrm{g}}$.

$$x_{new(i)}^{g}=\begin{bmatrix} x_{i}^{g}+rand\times x_{i}^{g}-x_{r}^{g} & if\ (x_{i}^{g}<x_{r}^{g}) \\ x_{i}^{g}+rand\times x_{r}^{g}-x_{i}^{g} & atherwise \end{bmatrix} \tag{3.66}$$

Where: If i ≠ r then

$\mathrm{x}_{(\mathrm{i})}^{\mathrm{g}}$= student

$x_{(r)}^{g}$ = another student.

Steps for the TLBO

The following steps are explanations to the TLBO algorithm.

- Initialize the population size or total of learners in the class (N) total of generations (G) total of design variables or subjects (courses) offered which coincides with the amount of units to place in the distribution system (D) and limits of design. The purpose of optimization problem as: Minimize f(X), where f (X) is the objective function X is a vector for design variables such that $L_l \leq x \leq U_l$
- Randomly selected population giving to the number of students in the class (N) and number of subjects presented (D).
- Calculate the mean of each subject presented in the category.
- Supposed on grade of students from maximum to minimum range.
- Modification score of every subject for the individual student.
- Every learner modification score of every subject through the mutual interaction with the further learners. Every learner interacts subjectively with anther learners and thus facilitates information sharing.

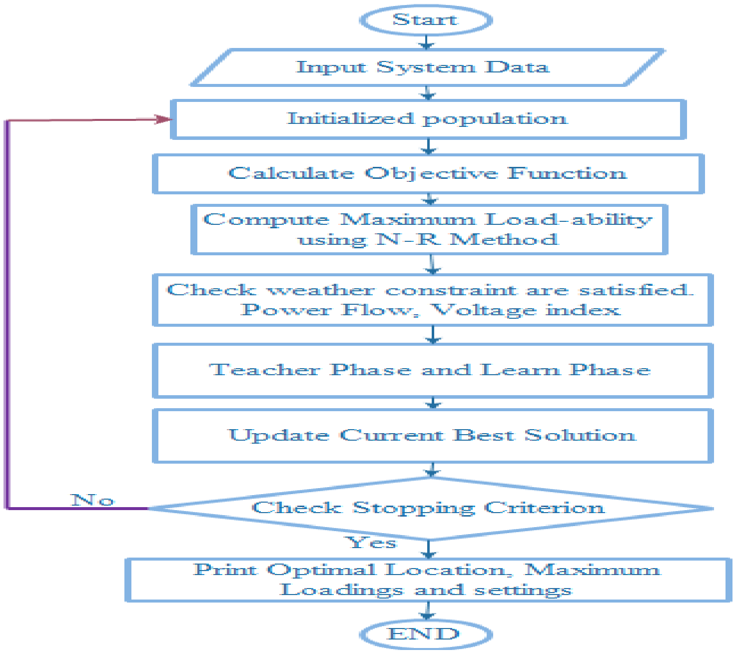


Figure 3.11: TLBO algorithm flow chart for transmission network

3.10.2. Particle Swarm Optimization

Particle swarm optimization (PSO) is a Meta heuristic algorithm based on the concept of swarm intelligence. PSO proposed by Eberhart and Kennedy in 1995, considering social behavior in the flocks of birds that flew together in [74]. It takes its operation based on the movement of organisms and social behavior of animals such as birds, fishes, insects, their communities, and the members of the entire population maintained through the search procedure.

PSO focused on how they manage as a group, rather than as individuals, recreating themselves and adapting in accordance with the changes in the surrounding environment, to search for food or to migrate. It was imitated the behavior of individual swarms which are a flock of birds, school of fish, and other insect groups and optimizes a problem by improving, in an iterative way, candidate solutions called particles regarding a given measure of quality.

In a PSO algorithm, the particle is an individual member & each particle flies around the multi-dimensional search space with a velocity and position. The particle updates its velocity and position continuously comparing itself with its own experience and experience of the neighbor's particles or the experience of the whole swarm. Then each particle moved through the information related to best personal position (Pbest) and best global position (Gbest). The mathematical expression of the algorithm also expressed in the following equations.

$$V_i^{(k+1)} = V_i^k + c_1 * r_1(X_{Pbest} - X^k) + c_2 * r_2(X_{Gbest} - X^k) \qquad (3.67)$$

$$X_i^{(k+1)} = X_i^k + V_i^{(k+1)} \qquad (3.68)$$

Where;

X_i^k is the current individual position of particle i at iteration k

X_i^{k+1} is modified position of particle i

V_i^k is the velocity of particle i of the previous vector at iteration k

V_i^{k+1} is modified velocity of particle i

c_1, c_2 are random number between [0 1]

$X_{P\,best}$ is the personal best position of a particle

X_{Gbest} is the global best position of the particle

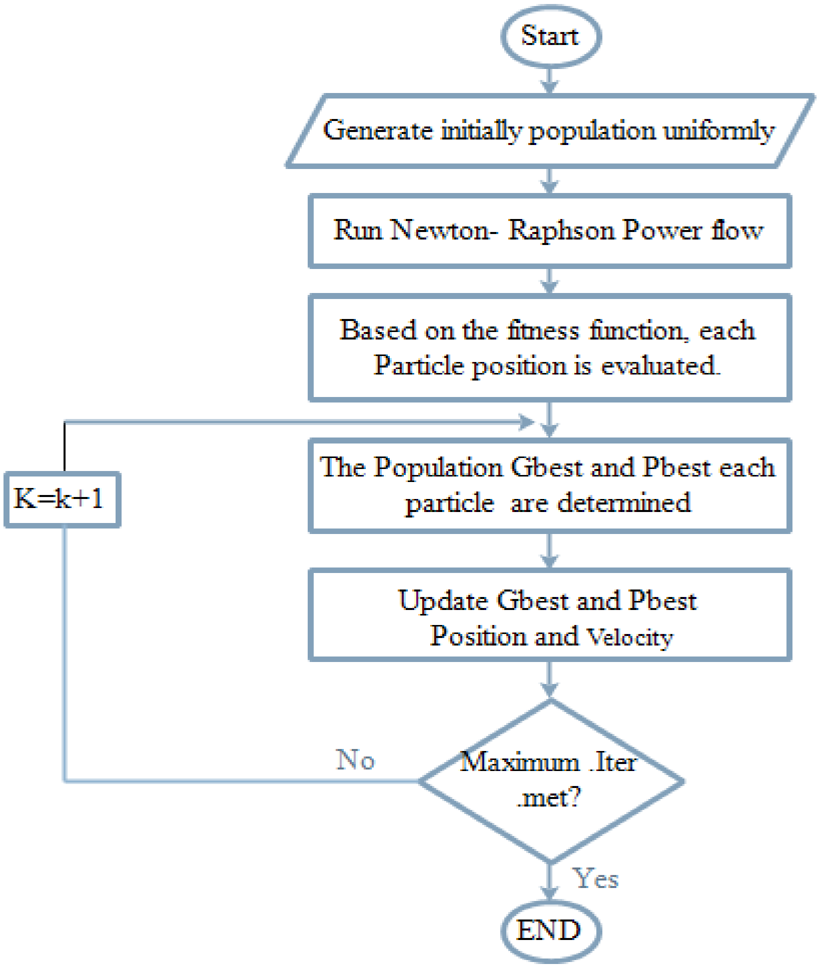


Figure 3.12: PSO algorithm flow chart for transmission network

3.10.3. Genetic Algorithm Control Techniques

The Genetic Algorithm (GA) is a type of evolutionary algorithm. Prof. John Holland (Holland, 1975) used the genetic algorithm for the first time in [75]. GA typically provides approximations to various problems. GA employs a variety of biological techniques, including inheritance, selection, crossover or recombination, mutation, and reproduction.

The various steps involved in this algorithm are:

- Define an initial population randomly or heuristically.
- Calculate the fitness value for every member inside the population.
- Assign the selection probability for every member in such a way that it is proportional to its fitness value.
- Formulate the next generation from the current generation by selecting the desired

individuals to produce off springs.

- Repeat the steps until suitable solution is found.
- GA defines a collection of particles known as population and each individual particle is called as chromosome.

These chromosomes are then evaluated using the cost function also known as the fitness function. The cost function is usually the objective function of the given problem. Some of the processes associated with GA are:

a) Selection – This process is commonly used to select the chromosome that will reproduce based on the fitness criterion.

b) Reproduction – This step is used to create the next generation from the current one.

c) Crossover – This procedure is used to transfer genetic material between chromosomes. It is possible to use a single or multiple point crossover.

d) Mutation – This process results in a change in chromosomes for a single person. Mutation keeps the algorithm from becoming stuck at a specific point.

e) Stopping criteria – this is the final step in GA. The iteration stops when it reaches a desired solution or it achieves the maximum number of cycles.

Implementation Algorithm: Using a predefined fitness function, GA results in the formation of fittest members after each iteration. The basic flow chart of the Genetic Algorithm is shown in Figure 3.13 ahead.

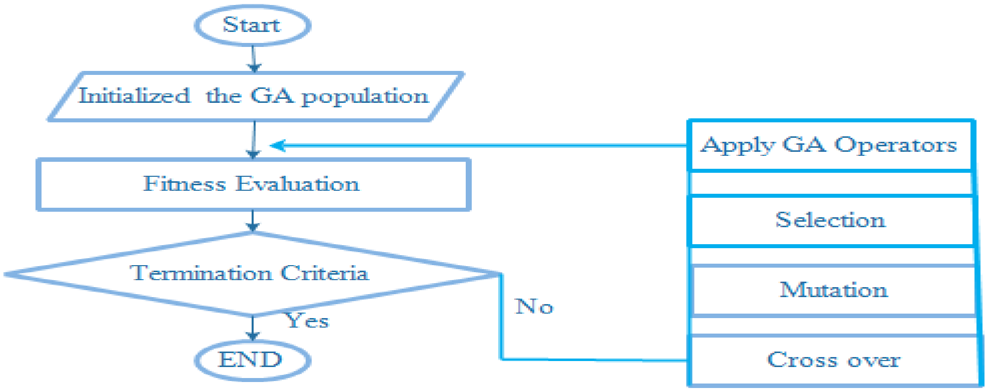


Figure3.13: Flowchart basic implementation of GA algorithm

CHAPTER FOUR

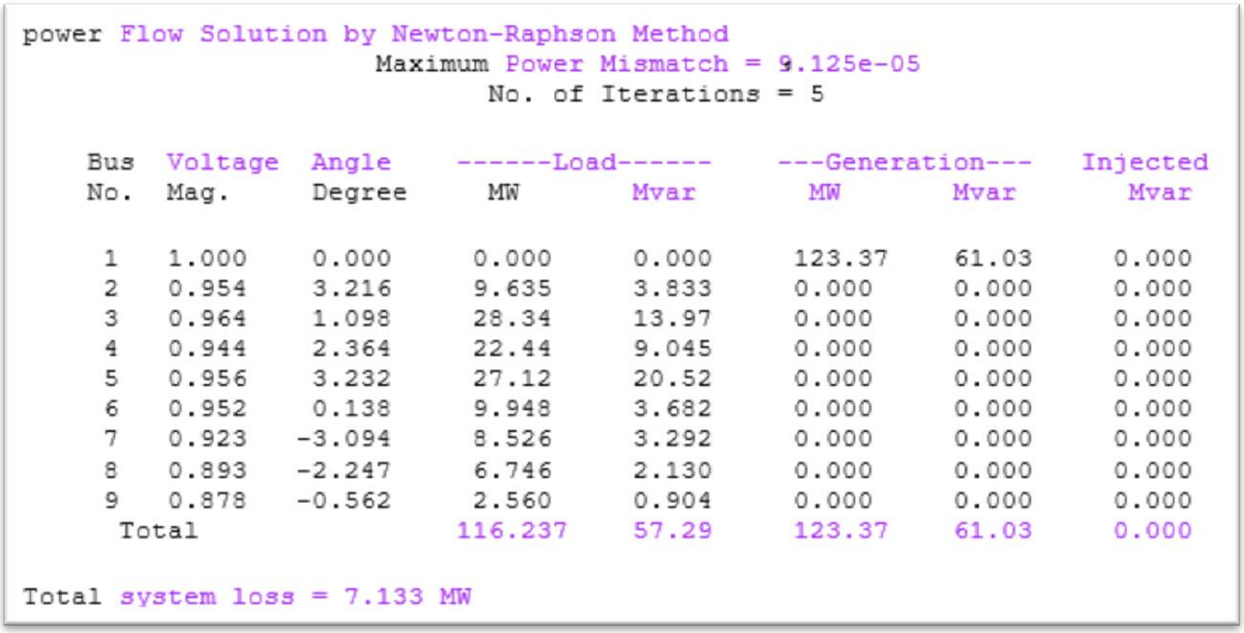
4. RESULT AND DISCUSSION

4.1. INTRODUCTION

This thesis work performed on the transmission network of the Alaba to Bukuluguma transmission system. This chapter begins by describing the performance of the Alaba to Bukuluguma transmission network without the installation of STATCOM. The total active and reactive power supply of the system is 123.37MW and 61.030 MVAr respectively.

The findings of a load flow analysis of an Alaba to Bukuluguma transmission network done in the MATLAB environment to determine the system steady state and compare it to IEEE standards are shown in Table 4-1.

Table4-1: load flow analysis of an existing network



```
power Flow Solution by Newton-Raphson Method
                      Maximum Power Mismatch = 9.125e-05
                             No. of Iterations = 5

    Bus  Voltage  Angle    ------Load------    ---Generation---   Injected
    No.  Mag.     Degree     MW       Mvar       MW       Mvar       Mvar

     1   1.000    0.000    0.000     0.000     123.37    61.03      0.000
     2   0.954    3.216    9.635     3.833     0.000     0.000      0.000
     3   0.964    1.098    28.34     13.97     0.000     0.000      0.000
     4   0.944    2.364    22.44     9.045     0.000     0.000      0.000
     5   0.956    3.232    27.12     20.52     0.000     0.000      0.000
     6   0.952    0.138    9.948     3.682     0.000     0.000      0.000
     7   0.923   -3.094    8.526     3.292     0.000     0.000      0.000
     8   0.893   -2.247    6.746     2.130     0.000     0.000      0.000
     9   0.878   -0.562    2.560     0.904     0.000     0.000      0.000
      Total                116.237   57.29     123.37    61.03      0.000

Total system loss = 7.133 MW
```

The suggested technique is employed in this chapter for optimal STATCOM placement and size at the node with the least amount of power loss and the lowest bus voltage, as shown in the following result analysis. Matlab 2016 was used to implement and program the method described in the preceding chapter. Appendix A contains the main codes that were programmed according to the proposed algorithm's implementation steps. The results are divided into sections based on the fitness function system being considered and the size of STACOM that is being placed optimally. Different comparisons have also been made between this algorithm and other algorithms in the open literature to show the reliability of this algorithm in reducing real and reactive network losses and improving bus voltage.

Using the AI technique ANN to develop a control plan for the proposed STATCOM, this is based on the PI controller gains' optimal values.

4.1.1. Description of Optimization Algorithm Parameters

With the preferred objective functions, the proposed algorithm is used to reduce power loss and increase the voltage stability margin. The optimization-based technique is run multiple times on different optimal parameter settings, as illustrated in Table 4-2.

Table 4-2: shows the TLBO algorithm's parameters.

Population size	Max.number of iteration	Teaching Factor	Design Variable
100	100	Round[1+round(0,1) {2-1}	Vary

4.1.2. Simulation Results of Alaba to Bukuluguma Transmission System

The load-flow analysis was done using the Newton Raphson load flow method, and the initial power loss, bus voltage, and voltage stability index of the system were determined using the line and bus data of the Transmission network. A bus-based voltage index study prompted the TLBO algorithm to find the best location and size for the STATCOM. Two possible situations are examined for the implementation of the stated method based on the simulation results for the suggested system, as shown below.

Case 1: Load Flow Analysis before Installing STATCOM Device in the System.

Load flow Newton Raphson analysis method is applied to find the bus voltage magnitudes, Stability indexes of line and transmission line loss.

To study and acquire the steady state bus voltages, active and reactive flow in the network, Newton-Raphson power flow was used. The voltage magnitude and line losses were noted for discussion and are now provided. The bus voltage magnitude results for the network's power flow study are shown in Table 4-3.

Table 4-3: Bus voltage magnitudes of existing network

Bus No	Bus Type	Bus Voltage Magnitude (p.u)
1	Slack	1.000
2	P-V	0.954
3	P-V	0.964
4	P-Q	0.944
5	P-V	0.956
6	P-Q	0.952
7	P-Q	0.923
8	P-Q	0.893
9	P-Q	0.878

It was noted in Table 4-3, that the voltage magnitudes at 4, 7, 8, and 9 are out of voltage limit. This was not connected with lack of load connection at bus 4, 7, 8, and 9. This situation must be prevented to avoid cascading bus voltage violation which might lead to system collapse.

Therefore, there is need to incorporate STATCOM to control this bus voltage stability, hence, these buses whose terminal voltages are violated are the candidates for STATCOM device placements.

Figure 4-1 depicts the graphical interpretation of bus voltage magnitude after the simulation without STATCOM device. The low bus voltage occurs at bus 4, 7, 8 and 9 as earlier stated. Apart from swing bus whose value remains constant at 1.00 volts even after the simulation, other bus voltages are within the allowable limits.

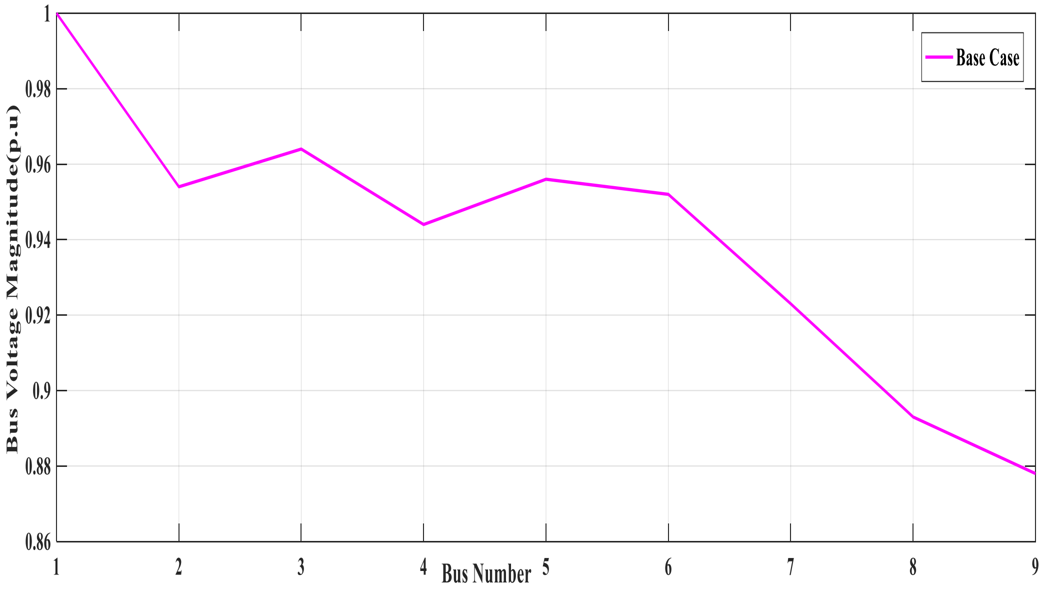


Figure 4-1: Bus Voltage Magnitude of System before STATCOM Placement

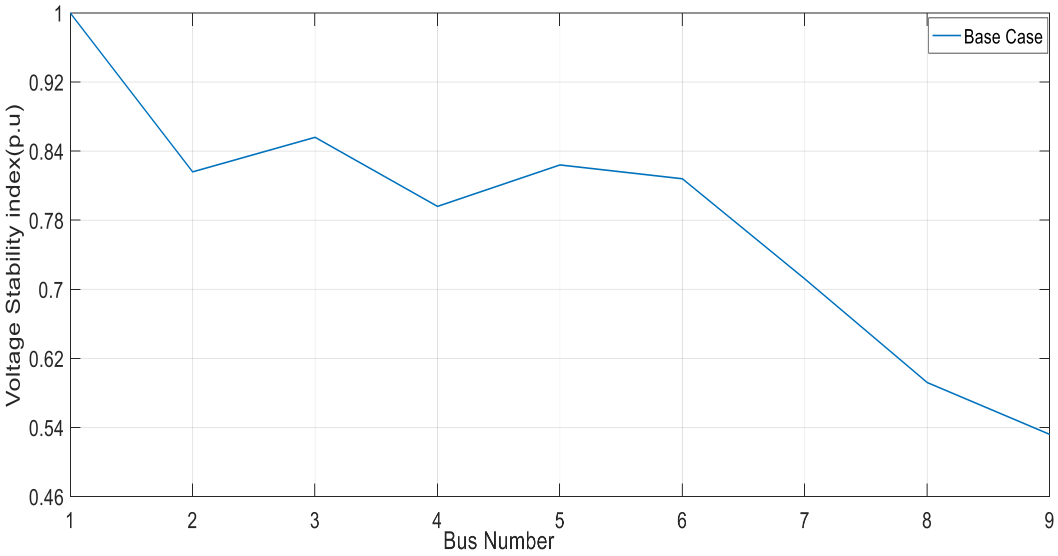


Figure4-2: Base case voltage stability index before compensation

Figure 4-1 and figure 4-2 shows bus voltage magnitude of each bus existing in the transmission system and voltage stability index of the system respectively.

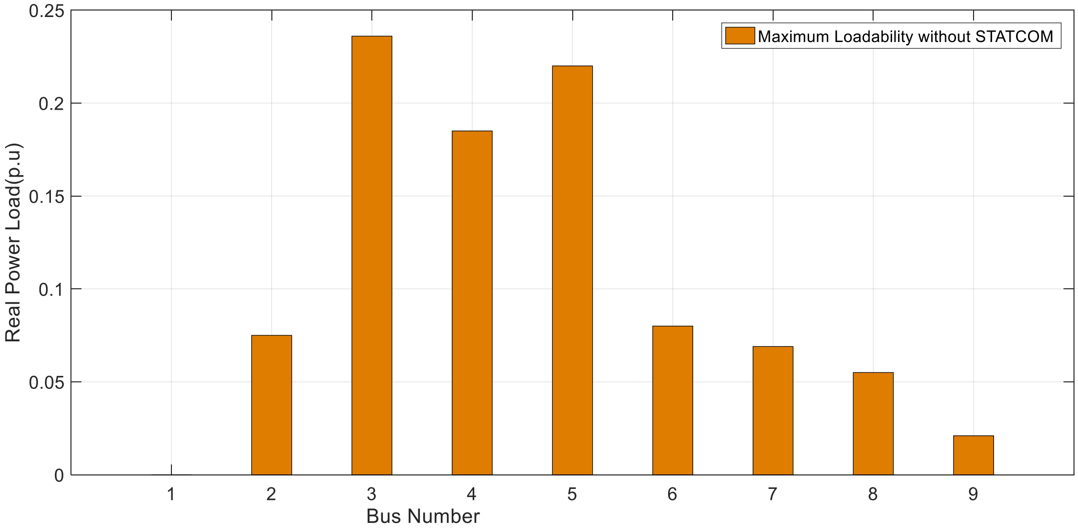


Figure 4-3: Load levels before STATCOM placement

Table 4-4 includes the following values. The transmission network from Alaba to Bukuluguma has a total real power loss of 7.133 MW and a reactive power loss of 3. 659MVAr. For a better understanding, consider Figure 4-4, which illustrates the graphical representation of losses in Table 4-4. There is a power loss on lines 1–2, 2–3, 3–4, 4–5, 5–6, 6–7, 7–8, and 8–9. These losses are having a negative effect on the network's performance.

Table 4-4: Line Losses of Existing Transmission Network (Without STATCOM)

Bus number		Stead state	
From Bus	To bus	MW	MVar
1	2	0.5744	0.3769
2	3	0.8234	0.6293
3	4	0.9562	0.5542
4	5	0.8765	0.4931
5	6	0.9624	0.5656
6	7	0.9755	0.3783
7	8	0.9861	0.3199
8	9	0.9896	0.3420
Total Power Losses		7.133	3.659

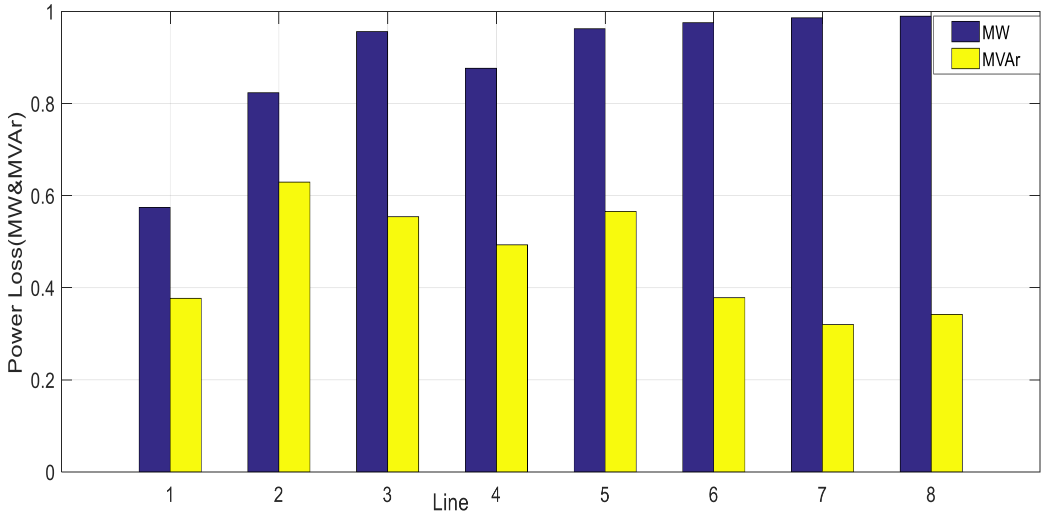


Figure 4-4: Real and Reactive Power Loss before STATCOM Placement

The status of the transmission system before optimization

Table 4-5: The status of the transmission system before optimization.

Parameters	
Active Power Loss(MW)	7.133
Reactive Power Loss(MVAr)	3.659
Minimum Bus Voltage(p.u)	0.878
Minimum voltage stability index(p.u)	0.52
Maximum Bus Voltage (p.u)	1.000
Maximum voltage stability index(p.u)	1.000

Case 2: Load Flow Analysis after Installing STATCOM Device in the System

Table 4-6: Bus Voltage magnitude of System after STATCOM Placement

Bus No	Bus Type	Bus Voltage Magnitude (p.u)
1	Slack	1.000
2	P-V	0.956
3	P-Q	0.976
4	P-Q	0.956
5	P-V	0.968
6	P-Q	0.964
7	P-Q	0.935
8	P-Q	0.905
9	P-Q	0.922

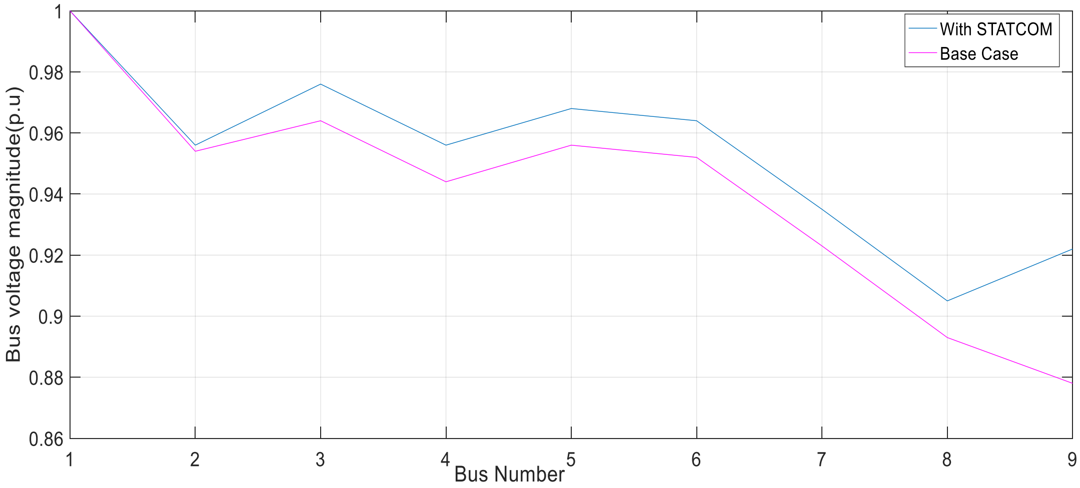


Figure 4-5: Bus Voltage Magnitude Comparison Without and with STATCOM Placements

The voltage magnitude comparison before and after STATCOM device placement is presented in Table 4-6. The results of the line losses for power flow analysis of the system are presented in Table 4-7. The total loss was reduced from 7.133 to 5.176 MW. With this manual placement, a real power loss reduction of 1957 kW was achieved. This was as a result of installing of STATCOM device in the system which generated required reactive power to control the load flow and loss minimization.

Table 4-7: Results of the Line Losses with STATCOM

Bus number		With STATCOM	
From Bus	To Bus	MW	MVar --
---1	2	0.4272	0.2319
2	3	0.6245	0.4011
3	4	0.6967	0.3957
4	5	0.6507	0.4264
5	6	0.6871	0.2956
6	7	0.6367	0.3142
7	8	0.6857	0.302
8	9	0.7671	0.3951
Total Power Losses		5.176	2.862

Likewise, there was a reactive power loss reduction of 797 kVar when STATCOM was installing in the network. This was possible because of capability of STATCOM to generate or consume reactive power on any connected network. The graphical presentation losses of all the lines are shown in Figure 4-6.

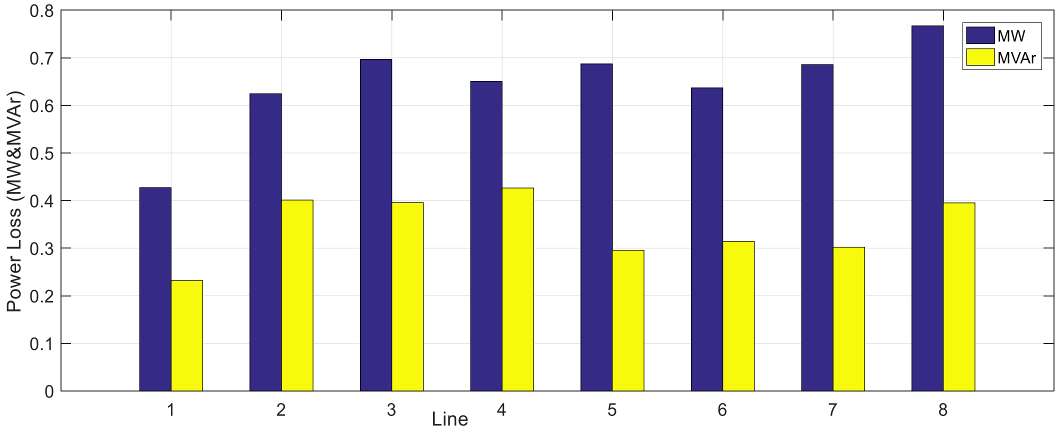


Figure 4-6: Real and Reactive Power Loss after STATCOM Placement

Figure 4-6 shows the total loss before and after the STATCOM devices were installed. With the STATCOM device, a 21.8% reduction in reactive power loss was realized in this study. Because bus terminal voltage is directly related to the quality of network reactive power, this reactive power regulation effectively improved network performance. At the same time, a 27.4 % reduction in active power loss was obtained.

The release of 1957 kW active powers back to the network is an advantage for a system that is being operated at threshold. It is worthy of note that reactive power loss reduction is quite significant compare to active power loss reduction, howbeit, this is in accordance to the shunt FACTS device used whose operations directly rely on reactive power manipulations. Nevertheless, the focus of the exercise which is the minimization of transmission line losses with STATCOM placement was achieved.

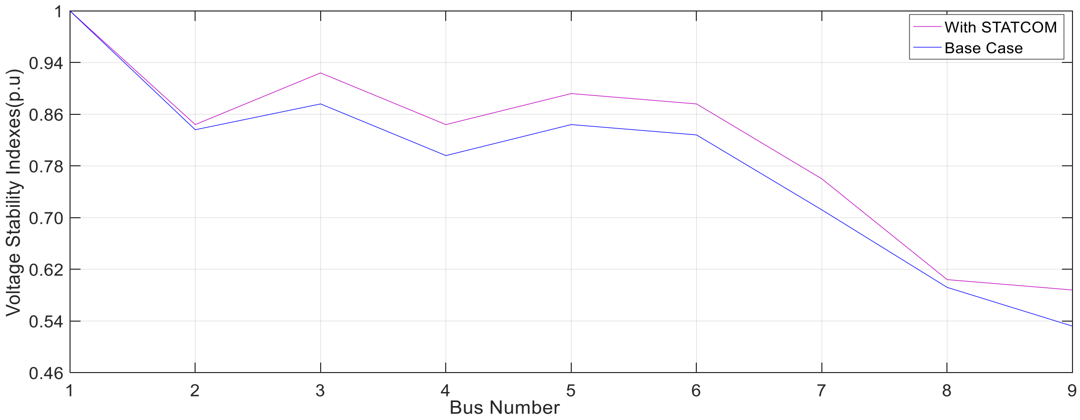


Figure4-7: Voltage stability index before and after compensation

Case 3: Load Flow Analysis after Installing STATCOM Device and set with TLBO in the System.

The simulation results are presented in this part to show the influence of single STATCOM allocations in the network on minimizing power loss and voltage stability margin improvement. Following the base case analysis, the conventional TLBO provided to search for the optimal size and position of STATCOM in the real network. For each bus level, the optimal STATCOM size was determined to be 25MVar, and the optimal sites were found to be bus 4.

The STATCOM device installed enhanced network bus voltage magnitude by allowing voltage magnitudes at the majority of the buses to be within a (0.95-1.05) range. However, for this test instance, the magnitude of voltage at bus numbers 8 and 9 was enhanced from 0.893 to 0.905 and 0.878 to 0.922 p. u, respectively. This bus terminal voltage was severely affected, and it violated the bus voltage limit. As a result, the TLBO algorithm was utilized to best position and size STATCOM device in order to restore this terminal voltage within the limit.

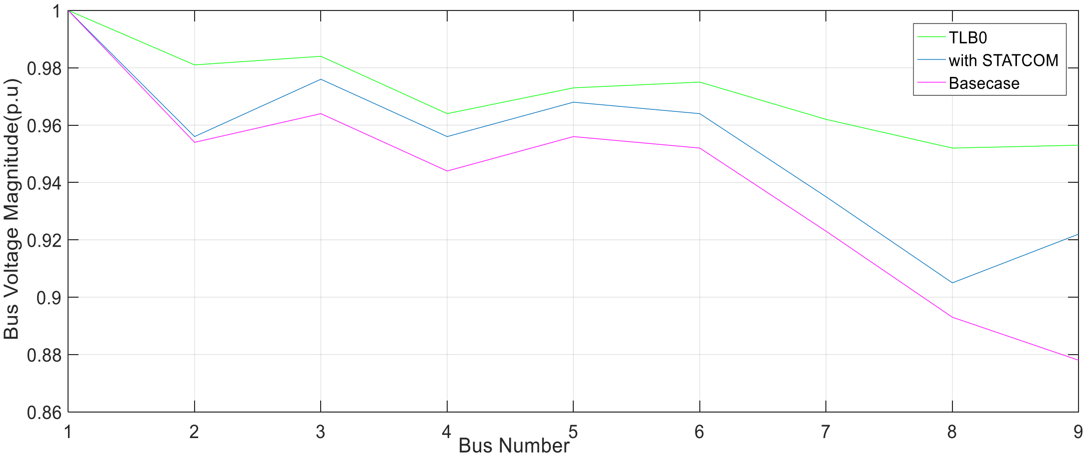


Figure 4-8: Bus Voltage Magnitude for all the three test case

Table 4-8: Bus Voltage Magnitude for TLBO case

Bus No	Bus Type	Base Case Bus Voltage Magnitude (p.u)	TLBO case Bus Voltage Magnitude (p.u)
1	Slack	1.000	1.000
2	P-V	0.954	0.981
3	P-V	0.964	0.984
4	P-Q	0.944	0.964
5	P-V	0.956	0.973
6	P-Q	0.952	0.975
7	P-Q	0.923	0.962
8	P-Q	0.893	0.952
9	P-Q	0.878	0.953

STATCOM with TLBO assures that no more bus voltage limits violations occur on any of the buses. The adoption of this improves the total magnitude of the network bus voltage even more. Figure 4-8 shows the bus voltage magnitude comparison for the three test conditions. When STATCOM was properly positioned with TLBO, the improvement recorded with manual selection of the STATCOM parameter resulted in an improvement of bus voltage magnitude but bus voltage enhancement.

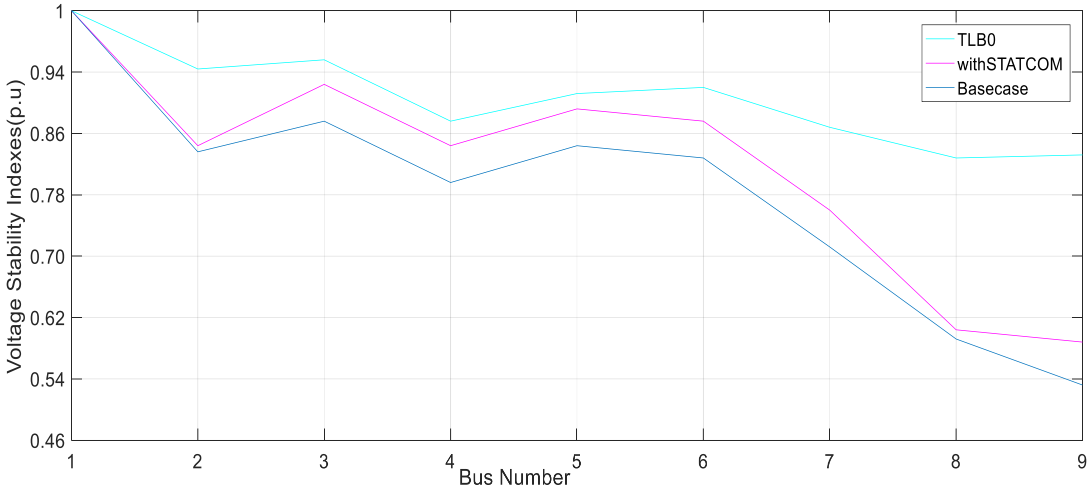


Figure4-9: Voltage stability index before and after compensation

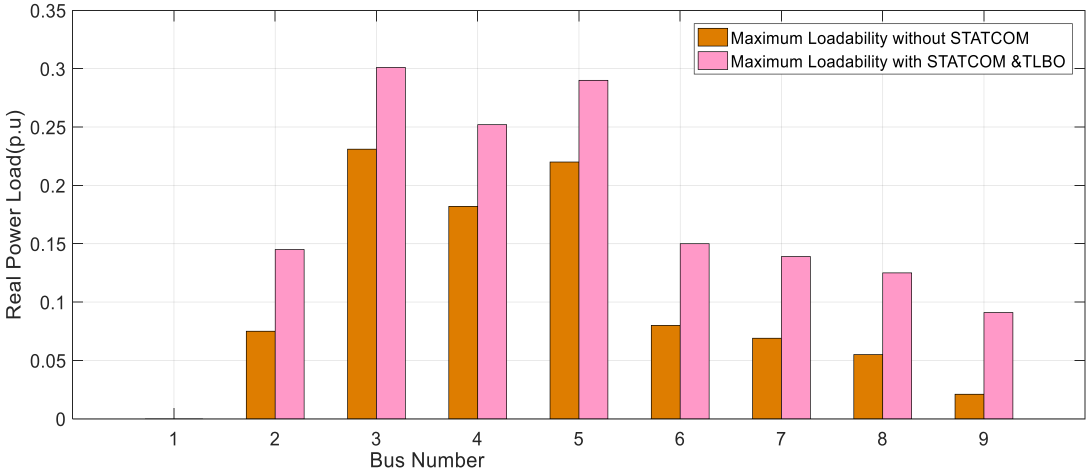


Figure4-10: Load levels after STATCOM placement

4.2. Minimization of Active Power Loss

STATCOM device was able to minimize real power losses by using optimization algorithms for placement technique.

Table 4-7 shows the real power loss details for the base case, TLBO placed STATCOM device. The total real power loss without any device is 7.133 MW in the base case, but it was reduced to 4.292 MW in the advanced case.

Table 4-9: Active power Loss Reduction result for TLBO case

Bus number		Stead state Case	TLBO Case
From Bus	To bus	MW	MW
1	2	0.5744	0.3221
2	3	0.8234	0.5122
3	4	0.9562	0.5342
4	5	0.8765	0.5431
5	6	0.9624	0.6106
6	7	0.9755	0.5783
7	8	0.9861	0.5592
8	9	0.9896	0.6325
Total Active Power Losses		7.133	4.292

When using the TLBO optimization algorithm to install the STATCOM, a reduction of 2.841 MW was realized. The usage of TLBO to integrate the STATCOM device resulted in a 39.8% reduction in active power loss.

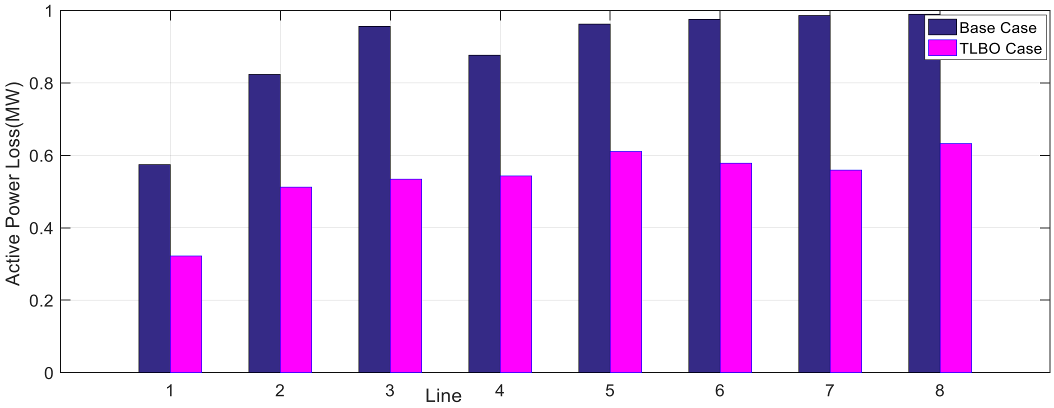


Figure4-11: Active power loss result for TLBO case

4.3. Minimization of Reactive Power Loss

STATCOM device was able to minimize reactive power losses by using optimization algorithms for placement technique. Table 4-8 shows the reactive power loss details for the base case, TLBO placed STATCOM device. The total real and reactive power loss without any device is 3.659 MVAr in the base case, but it was reduced to 2.028 MVAr in the advanced case.

Table4-10: Reactive Power Loss Reduction for TLBO case

Bus number		Stead state Case	TLBO Case
From Bus	To bus	MVAr	MVAr
1	2	0.3769	0.117
2	3	0.6293	0.355
3	4	0.5542	0.279
4	5	0.4931	0.347
5	6	0.5656	0.208
6	7	0.3783	0.279
7	8	0.3199	0.155
8	9	0.3420	0.288
Total Reactive Power Losses		3.659	2.028

When STATCOM was placed under case two study, the reactive loss, which was 3.659 MVAr without the device, was reduced to 2.862 MVAr. When STATCOM was optimally installed using TLBO, this was further reduced to 2.028 MVAr. When TLBO was used to put the device and when the device was manually placed, 0.797 and 1.631 MVAr were achieved, resulting to 21.8 % and 44.6% overall reductions, respectively.

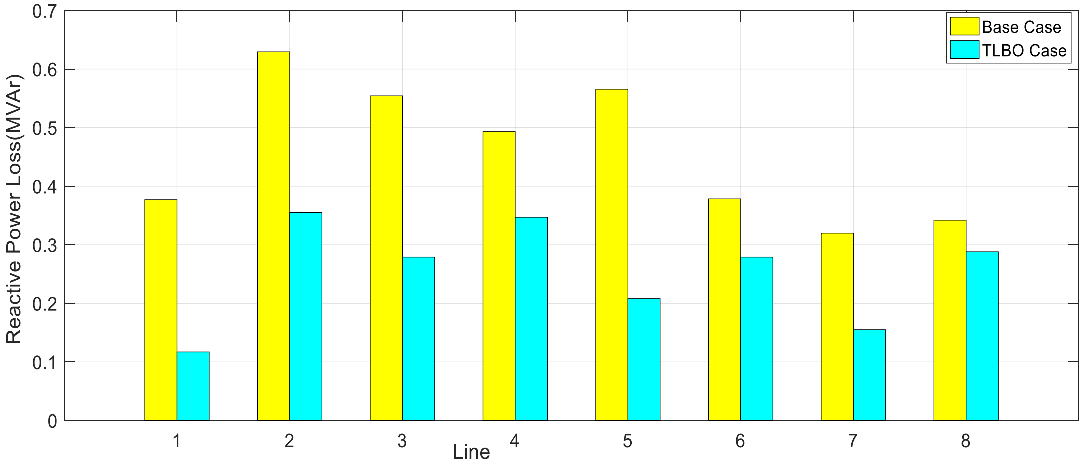


Figure 4-12: Reactive power loss reduction for TLBO case

4.4. Cost Calculation

4.4.1. Financial Losses Analysis

For the two scenarios considered in this study, the annual energy of power loss can be calculated as follows:

Case 1: Financial Losses of the system before installation of STATCOM

Scenario 1: Annual MWh loss for 7.133 MW

= (peak Loss in MW) *8760h

= 62,485.080MWh

Case 2: Financial Losses of the system after installation of STATCOM

Scenario 1: Annual MWh loss for 4.292MW

= (peak Loss in MW) *8760h

= 37,597.920MWh

4.4.2. Cost Implication

The cost analysis is based on Ethiopian Electric Utility's ETB/kWh energy rates under the new power tariff. By averaging all tariff class energy unit costs (ETB/kWh), the cost of energy is calculated to be 2.0343 ETB/kWh or 2034.3 ETB/MWh. The total amount of annual financial loss due to power loss is calculated using the 2034.3 ETB/MWh rate.

Case 1: Cost implication of the system before installation of STATCOM

The annual financial loss in scenario 1 is 62,485.080 MWh *2034.3 ETB/MWH, or 127,113,398.2 or approximately 127.113 million ETB.

Case 2: Cost implication of the system after installation of STATCOM

For scenario 1, the annual financial loss is 37,597.920 *2034.3 ETB/MWh, or 76,485,448.66 ETB, or approximately 76.485 million ETB.

Table 4-11: cost comparison before and after STATCOM

Cos before STATCOM (ETB/Year) (A)	Cost after STATCOM (ETB/Year) (B)	Saving (ETB/year) (A-B)	Cost of STATCOM (ETB/Year)
127,113,398.2	76,485,448.66	50,627,949.54	66,010000

4.4.3. The cost of a STATCOM rating

Despite the fact that FACTS controllers can provide high-speed control for improving electric power systems, one key disadvantage of power electronic-based controllers is that they cost more per unit of rating than comparable conventional equipment. The expenses of the various FACTS controllers are shown in Table 4-12 in [44]

Table 4-12: Comparison of cost of shunt devices

SHUNT DEVICES	**COST (US $)**
Shunt capacitor	8 / kVar
SVC	40 / kVar
STATCOM	50 / kVar

The costs for STATCOM in the following scenarios are tabulated in Table 4.11, based on Table 4-12 and the Commercial Bank of Ethiopia's exchange rate of one US Dollar = 47.15 Ethiopian Birr (ETB) on October 30, 2021 G.C.

4.4.4. Costs of STATCOM using TLBO

Table4-13: cost of STATCOM

Size of STATCOM(MVAr)	25
Cost of STATCOM in US Dollar	50
Investment cost($/KVAr)	1,250,000
Installation cost (10%)	125,000
Annual maintenance cost (2%)	25,000
Total cost in US Dollar	1,400,000

4.4.5. Payback Period

The Payback Period is the number of years of benefits needed to break even on a project.
The following equation can be used to calculate the payback time.
The project cost (ETB/Year) divided by the birr saved (ETB/Year)

Payback Period =Cost of STATCOM/Saving=66,010000/50,627,949.54=1.304years

4.5. Comparison of different optimization algorithms with STATCOM placement

In this study under the normal load conditions, the results obtained using the TLBO techniques are compared with GA and PSO optimization techniques.
After installing the STATCOM, the overall bus voltage magnitude of the network has been improved by 6.1% by TLBO, 3.9% by PSO, 3.8% by GA.

The minimum bus voltage magnitude ($0.878\ \mathrm{p.u}$) obtained at bus 8 from the base case analysis has been improved to $0.932\ \mathrm{p.u}$, 0.933p.u and $0.9531\ \mathrm{p.u}$ with the proposed GA, PSO and TLBO techniques. The percentage reduction in active power loss for the GA, PSO and proposed TLBO techniques are approximately 34.5%, 36.6%, and 39.8 % as compared to the base case and reactive power loss for the GA, PSO and TLBO are approximately 36%, 38.2% and 49.3%.

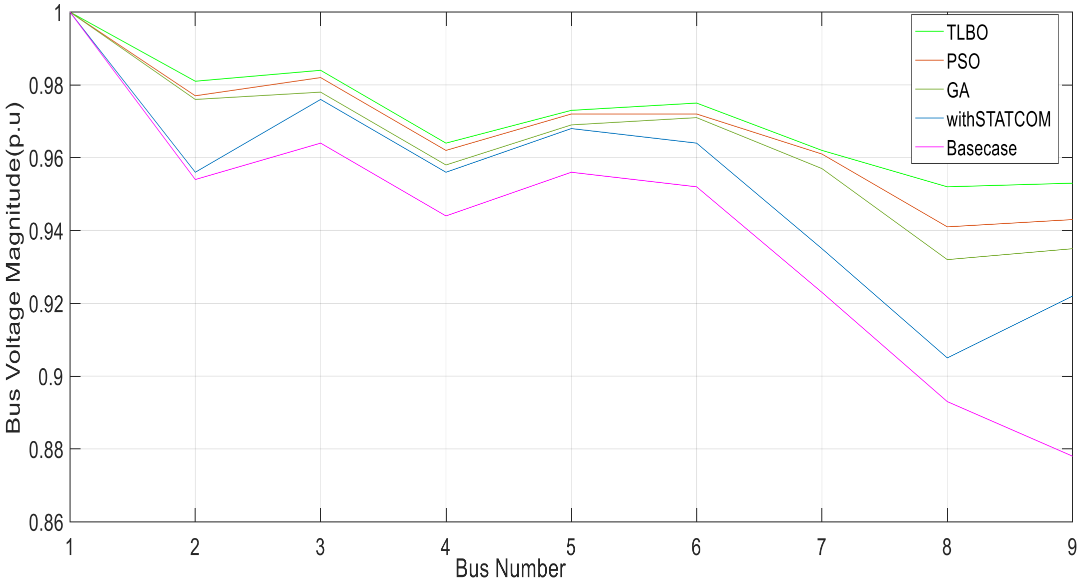


Figure4-13: Comparison of bus voltage different optimization algorithms with STATCOM placement

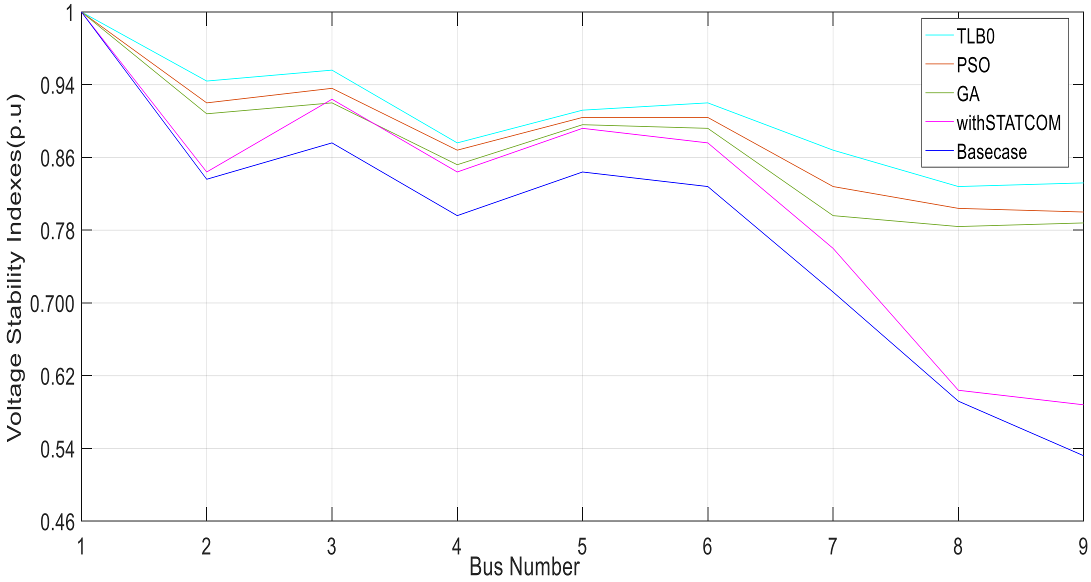


Figure 4-14: Comparison of voltage stability index different optimization algorithms with STATCOM placement.

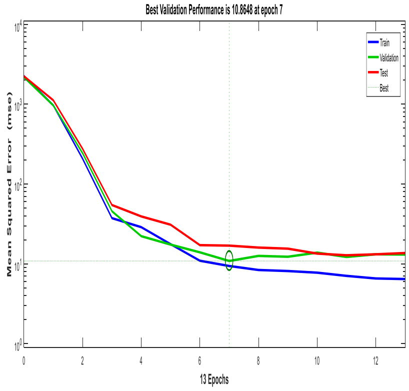
Table 4-14: Summary of Simulation Results for the using optimization algorithms

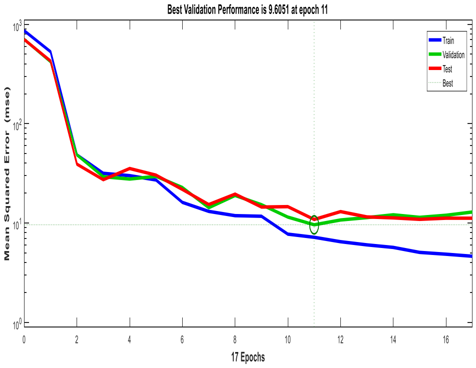
Parameters	**Case I**	**Case II**		
	Base Case	GA	PSO	TLBO
Optimal bus location at	-	6	5	4
Optimal Size of STATCOM (MVAr)	-	25.8	25.5	25
Minimum Bus Voltage $(p.u)$	0.878	0.932	0.933	0.9531
Maximum bus voltage magnitude (p.u)	0.964	0.976	0.977	0.984
Overall Active Power Loss (MW)	7.133	4.673	4.521	4.292
Percentage Reduction in Active Power Loss (%)	-	34.5	36.6	39.8
Overall Reactive Power Loss (MVAr)	3.659	2.34	2.26	2.028
Percentage Reduction in Reactive Power Loss (%)	-	36	38.2	49.3

4.6. Dynamical Control of STATCOM using ANNs

TLBO is a tool for determining the best controller gain values. The ANN logarithm is used to test the controller and choose the gains constants based on the activation's elements. The eight controller constant networks are trained using the controller constants as inputs.

The training, validation, and test errors used to check the progress of training for eight trained networks are shown in below.





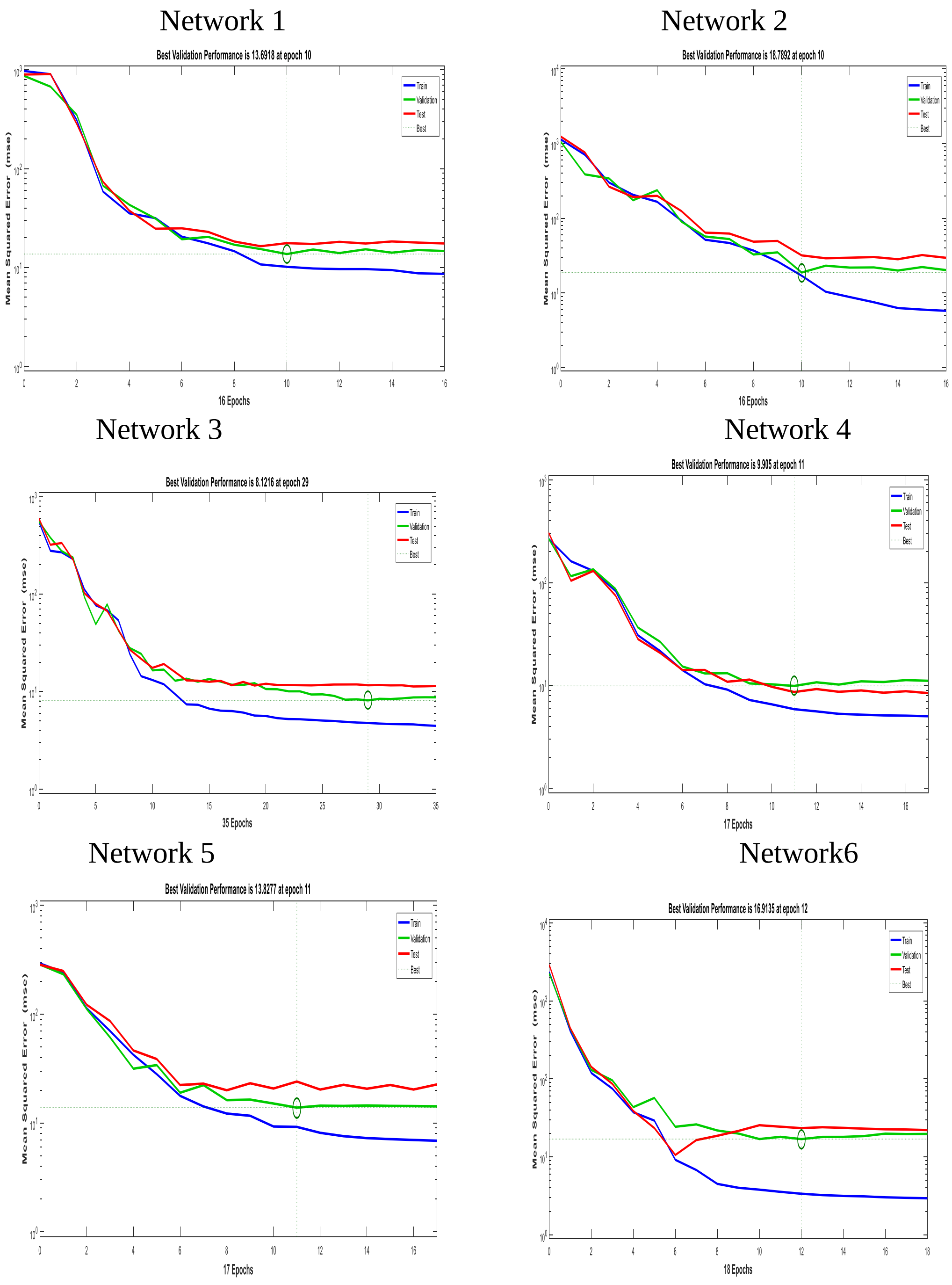
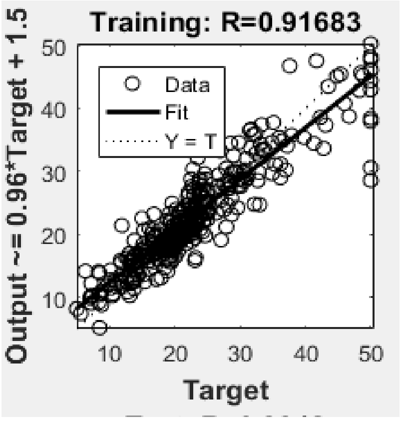
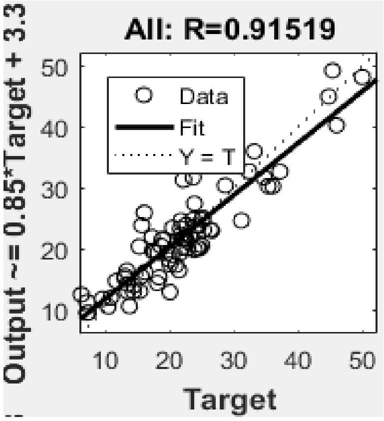


Figure4-15: Training validation and test curves for neural networks (1-8)

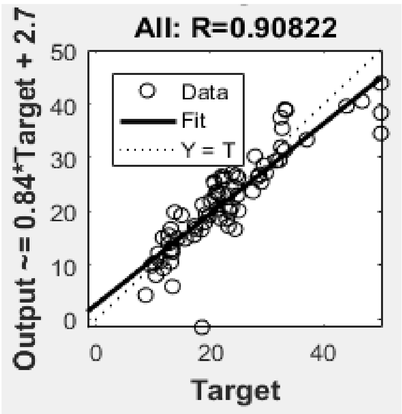
A solid line indicates a perfect match (output equal to aim). As seen in the table, the output appears to match the objectives precisely with regression. The R value represents the link between outputs and objectives. If R is close to zero, there is no linear relationship between outputs and targets; nevertheless, the research findings revealed that R is more than 0.75, indicating an appropriate link between outputs and targets for various neural trained networks.



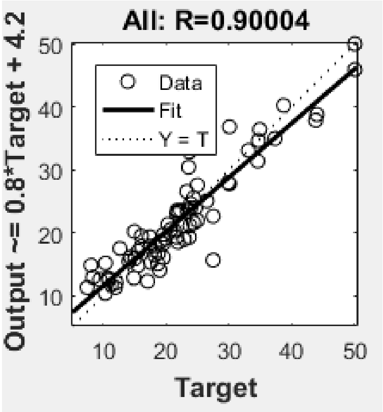
Network 1



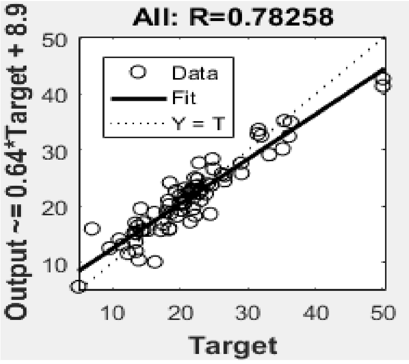
Network 2



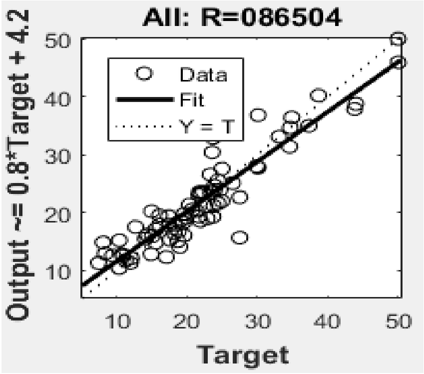
Network 4



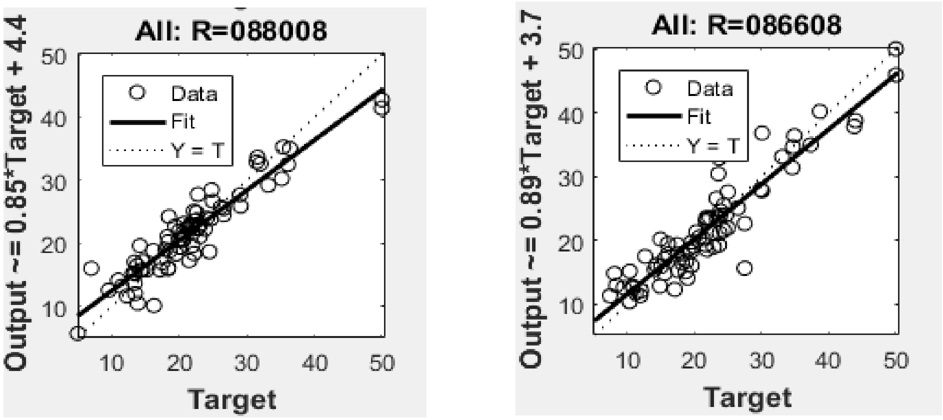
Network 5



Network 5



Network 6



Network 7 Network 8

Figure 4-16: Estimation and fitting for neural networks (1-8)

Table 4-15: MSE and R fitting function evaluation for eight neural networks

Neutral Network	Number of epochs	MSE	R
Network 1	7	0.79825	0.91683
Network 2	11	1.29632	0.91519
Network 3	10	3.89981	0.90822
Network 4	16	1.23115	0.90004
Network 5	29	1.32472	0.78258
Network 6	17	1.22551	0.86504
Network 7	6	0.1.143	0.88008
Network 8	12	1.3516	0.86608

Effect of ANN Controller on Performance of STATCOM for Improve the bus Voltage

The voltage deviation on the transmission bus is estimated to be around (0.02-0.05) pu. STATCOM controller gains are calculated for each created event using the TLBO algorithm, and the percentage error is calculated based on the optimization function's objective function. The results of STATCOM controller gains for the main steps disturbances of voltage violation events are shown in table 4-16 (see all data base for created events and optimal values for controller gains using TLBO in appendix B)

Table 4-16: Optimal STATCOM controller gain values during the main steps of voltage violation events using TLBO**.**

Event	Controllers	Kp	Ki
Voltage violation(0.878)p.u	Vac Regulator gains	10	3500
	Vdc Regulator gains	1e-3	10
	Current regulatory gains	1	100
	PLL Regulatory gains	7.13e2	3000

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This thesis presents an optimization approach for minimizing power transmission network losses and improving voltage profiles by properly sizing and locating STATCOM device.

The fundamental concerns that exist in the Alaba to Bukuluguma transmission system were addressed in this thesis, which included transmission network optimization and voltage profiles improvement. An objective function and a set of constraints are part of the optimization procedure. Load flow analysis, voltage stability analysis, TLBO, and ANN controllers are some of the basic methodologies employed in this research. To calculate the essential parameters in the existing transmission system, Newton Raphson load flow analysis was utilized.

The approach's efficacy and suitability for a steady-state constant load model were shown on a conventional IEEE 9-bus network in Alaba to Bukuluguma transmission network. The findings were compared to those produced using the traditional Genetic algorithm (GA) and particle swarm optimization (PSO) algorithms.

The existing system's total real power losses in the base case are 7.133 MW. The TLBO algorithm is utilized to choose design variables based on STATCOM's optimal placement and size. In terms of reducing both real and reactive power losses, the algorithm is found effective.

With the comparison of different system scenarios, the result demonstrates that loss reduction is significant. The reduction of actual power losses in the system is 39.8 percent, whereas the reduction of reactive power losses in network is 49.3 percent.

For all bus levels, the operated network's bus voltage has improved to within the allowed limit of IEEE range. After STATCOMs integration, the voltage stability index of the operating network improved compared to the base case. When compared to the network base-case results, the overall power loss was reduced by 39.8 percent and the bus voltage improved using the TLBO approach; for the GA approach, 34.5 percent reduction in total power loss was achieved; and for the PSO approach, 36.6 percent reduction in total power loss was achieved.

The applicability of TLBO, GA, and PSO for STATCOM location and parameter settings for the attainment of defined objectives was demonstrated by their successful independent implementation. STATCOM also played an important role in reducing network power loss and controlling bus voltage magnitude. However, the result showed using TLBO, GA, and PSO to optimize the STATCOM device has increased the transmission system's efficiency without the need for physical power infrastructure expansion. However, TLBO outperformed PSO in terms of performance, and GA is thought to be more successful for STATCOM device optimization to reduce power loss and improve bus voltage magnitude. It was shown that various research issues were properly addressed and that the implemented TLBO, GA, and PSO approaches were effective for optimal STATCOM device placement as compared to the uncompensated approach.

5.2. Recommendations

This research evaluates the influence of STATCOM on transmission network optimization and measures how much it impacts the systems by assessing the power loss and mitigating the power loss using STATCOM devices. Because the existing network topology is designed for the future of electric demand with the integration of STATCOM due to its costly nature, and the network of the system is altered by the integration of STATCOM, I strongly advise Ethiopian Electric Utility (EEU) to apply transmission network optimization using STATCOM to the Alaba to Bukuluguma transmission network system.

5.3. For future work

The following are some future research subjects:

(i) The ability and competence of this controller in affecting network parameters to meet target system objectives in steady state settings was demonstrated by the performance of an optimized STATCOM device in reducing network power loss and improving voltage stability margin. As a consequence, future research into STATCOM controller performance under various fault scenarios should be considered.

(ii) Various techniques for locating and sizing STATCOM controller optimally for example, cuckoo search algorithm, ant colony, tabu search algorithm among others on power transmission system should be investigated, analyzed and compared with the \sresults of this work.

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Appendix-A

```
%%%%%%%%% TLBO algorithm
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function TLBO(obj_fun, note1, note2)
format long;
nbus=9;
voltage_minimum=0.95;
voltage_maximum=1.05;
capmaxsij_maximum=125;
QMIN_VALUE=20;
QMAX_VALUE=100;
data_pass_to_loadflow{1}=voltage_minimum;
data_pass_to_loadflow{2}=voltage_maximum;
data_pass_to_loadflow{3}=capmaxsij_maximum;
data_pass_to_loadflow{4}=distmaxij_maximum;
%[finalres_base_case]=bold_flow_before;
if ~exist('note1', 'var')
 note1 = true;
end
if ~exist('note2', 'var')
 note2 = true;
end
[finalres_base_case]=bold_flow_before(voltage_minimum,nbus,d
ata_pass_to_loadflow);
[Students, select, upper_limit, lower_limit, ini_fun,
min_result, avg_result, result_fun, opti_fun,
result_fun_new, opti_fun_new] = Initialize(note1,obj_fun);
elite=0;
for COMP = 1 : select.itration
 for i = 1 : elite
 markelite(i,:) = Students(i).mark;
 resultelite(i) = Students(i).result;
 end
 for i=1:length(Students)
 cs(i,:)=Students(i).mark;
 cs_result(i)=Students(i).result;
 end
 cs;
 cs_result;
 for i = 1 : length(Students)
 mean_result=mean(cs);
 TF=round(1+rand*(1));
 [r1 r2]=sort(cs_result);
 best=cs(r2(1),:);
 for k = 1 : select.var_num
 cs_new(i,k)=cs(i,k)+((best(1,k)*TF*mean_result(k))*rand);
 end
```

```
 cs_new(i,:) = opti_fun_new(select, cs_new(i,:));
 cs_new_result(i) = result_fun_new(select, cs_new(i,:));
 if cs_new_result(i)<Students(i).result
 Students(i).mark =cs_new(i,:);
 cs(i,:)=cs_new(i,:);
 Students(i).result=cs_new_result(i);
 end
 hh=ceil(length(Students)*rand);
 while hh==i
 hh=ceil(length(Students)*rand);
 end
 if Students(i).result<Students(hh).result
 for k = 1 : select.var_num
 cs_new(i,k)= Students(i).mark(k) + ((Students(i).mark(k) - 
Students(hh).mark(k))*rand);
 end
 else
 for k = 1 : select.var_num
 cs_new(i,k)= Students(i).mark(k) + ((Students(hh).mark(k) - 
Students(i).mark(k))*rand);
 end
 end
 cs_new(i,:) = opti_fun_new(select, cs_new(i,:));
 cs_new_result(i) = result_fun_new(select, cs_new(i,:));
 if cs_new_result(i)<Students(i).result
 Students(i).mark =cs_new(i,:);
 cs(i,:)=cs_new(i,:);
 Students(i).result=cs_new_result(i);
 end
 end
 n = length(Students);
 Students = opti_fun(select, Students);
 Students = result_fun(select, Students);
 Students = sortstudents(Students);
 for i = 1 : elite
 Students(n-(i-1)).mark = markelite(i,:);
 Students(n-(i-1)).result = resultelite(i);
 end
 if rand<1
 Students = remove_duplicate(Students, upper_limit, 
lower_limit);
 end
 Students = sortstudents(Students);
 [average_result, within_bound] = result_avg(Students);
 min_result = [min_result Students(1).result];
 avg_result = [avg_result average_result];
 Mark = (Students(1).mark);
```

```
 if note1
 disp([num2str(min_result(end))])
 disp([num2str(Mark)]);
 end
end
fprintf ('\n %e',min_result(end));
fprintf ('\n %6.10f',Mark);
out_put (note1, select, Students, within_bound, min_result);
Bestvalue=Mark;
Best_location=floor(avg_result);
fprintf ('\n The best location for stat is %d
\n',floor(Bestvalue(1)));
fprintf ('\n Optimum value for stat Function is %f (Mvar)
\n',Bestvalue(2));
finalresult_val=Bestvalue(1: select.var_num);
 sat_loc=round(finalresult_val(1));
 sat_SIZE=finalresult_val(2);
 sat_place=[S_loc;S_SIZE];

[finalres_after_comp]=bold_flow_after(voltage_minimum,sat_pl
ace,data_pass_to_loadflow);
 %% display final result display('TLBO RESULTS ');
POWER_LOSS_BASE_CASE=finalres_base_case{2};
VSI_MINIMUM_BASE_CASE=finalres_base_case{4};
Reactive_power_loss_base_case=finalres_base_case{5};
STATCOM_LOCATION=S_loc;
STATCOM_SIZE_MVAr=S_SIZE;
POWER_LOSS_WITH_STATCOM=finalres_after_comp{2};
Reactive_power_loss_with_STACOM=finalres_after_comp{5};
VSI_MINIMUM_WITH_STATCOM=finalres_after_comp{4};
VSI_MAXIMUM_WITH_STATCOM=finalres_after_comp{8};
Active_power_loss_percantage_reduction=(POWER_LOSS_BASE_CASE
_POWER_LOSS_WITH_STATCOM)/(POWER_LOSS_BASE_CASE)*100;
Reactive_power_loss_percenatge_reduction=(Reactive_power_los
s_base_case_Reactive_power_loss_with_STACOM)/(Reactive_power
_loss_base_case)*100;%
Minimum_voltage_base_case=finalres_base_case{6};
Minimum_voltage_after_statcom=finalres_after_comp{6};
Maximum_voltage_after_statcom=finalres_after_comp{7};
voltage_profile_base_case=finalres_base_case{5};
Bus voltage _after_statcom=finalres_after_comp{5};
voltage_stablity_index_base_case=finalres_base_case{4};
voltage_stablity_index_after_statcomT=finalres_after_comp{4}
;
Active_power_loss_buses_WITH_OUT_STATCOM=finalres_base_case{
9};
Active_power_loss_buses_WITH_STATCOM=finalres_after_comp{9};
```

```
Reactive_power_loss_buses_WITH_OUT_STATCOM=finalres_base_cas
e{10};
Reactive_power_loss_buses_WITH_STATCOM =
finalres_after_comp{12};
voltage_before_compensation=finalres_base_case{3};
voltage_stab_index_before_compensation=finalres_base_case{4}
;
voltage_after_compensation=finalres_after_comp{3};
voltage_stab_index_after_compensation=finalres_after_comp{4}
;
%figure, plot(1:nbus,voltage_before_compensation,'r')
%hold on, plot(1:nbus,voltage_after_compensation,'k')
%xlabel ('Bus Number')
%ylabel (' Bus Voltage magnitude')
%Grid on;
%legend ('BASE CASE','WITH STATCOM')
%title ('Bus Voltage magnitude of the System Before and
After Compensation')
%figure,
plot(1:nbus,voltage_stab_index_before_compensation,'r')
%hold on,
plot(1:nbus,voltage_stab_index_after_compensation,'k')
%xlabel ('Bus Number'); ylabel('Voltage Stability Index')
%Grid on;
%legend ('BASE CASE','WITH STATCOM')
%title ('Voltage Stability Index for All Buses')
Figure, plot(1:nbus,
Active_power_loss_buses_WITH_OUT_STATCOM,(MW)'r')
Hold on, plot (1: nbus,
Active_power_loss_buses_WITH_STATCOM,'k')
Xlabel ('Bus Number');
ylabel ('Active power loss(MW)')
Grid on;
Legend ('BASE CASE','WITH STATCOM')
Title ('Active power loss for All Buses')
```

----------------------------------%%%%%%ANN ---------------------------------------

```
%calling data from TLBO
function [F,erorr1]= track noise(y)
%main role of this controller is minimize of error
% Track the output of optsim to a signal of 1
% Variables a1 and a2 are shared with RUNTRACKLSQ
Kd =0 ;
% Compute function valuew
simout=sim( power_statcom_pwm2sagl844’);
m=length(voutrms(2000:end,2));
t=0:4e-6:5e-6*(m-1);
```

```
signal=sin(2*pi*50*t+asin(three_pahe(2000,2)));
e=sqrt(sum((signal-
three_pahe(2000,2)).^2)/length(voutrms(2000:end,2))) ; %
compute the error
erorr1=100*sum((1-
voutrms(2000:end,2)).^2)/length(voutrms(2000:end,2)) ; %
compute the error
assignin(base, erorr1,erorr1);
F= erorr1;
end
Target=table (:8);
Input=x;
net8= newff (Input, Target, [3],
{’tansig’,’tansig’},’trainlm’, learngdm mse );
% Define learning parameters
net. trainParam.epochs=1000; % Maximum number of epochs to
train
net. train Param. goal = 1e-12; %Performance goal
net.trainParam.lr=0.02;%Learning rate
net.trainParam.mc=0.6;%Momentum constant
net.trainParam.lr_dec=0.878; % Ratio to decrease learning
rate%
net.trainParam.max_fail=1000; %Maximum validation failures
net.trainParam.max_perf_inc=0.944; % Maximum performance
increase%
net.trainParam.min_grad=1e-10; %Minimum performance gradient
net. trainParam.show=300; %Epochs between displays (NaN for
no displays)
net. trainParam.time=inf;%Maximum time to train in seconds
find_gain_constants = train(net8,Input,Target);


------------------------------------------------------------
----
```

Appendix-B

Event	Vac(Kp)	Vac(Ki)	Vdc(Kp)	Vdc(Ki)	i(Kp)	i(Ki)	PLL(Kp)	PLL(Ki)	Error%
0.944	1e-2	9.4	1e-3	1e-1	1	1e3	1.8e2	2.13e1	9.959
0.942	9.4	2.1e3	1e1	1e-1	1	1.8e3	8.9e2	2.44e3	8.221
0.940	4.94	4.17e-3	3.65	2.2e1	8.6e1	1.84e1	1.81e2	1.4e3	8.652
0.938	1e-2	2.22e3	8.42	7.04	1.86	2.21e3	8.72e2	1.0e3	9.556
0.936	11	3500	2.24e3	8.24	7.76	1.75	2.33e3	2.01e3	8.435
0.934	9.6	3500	9.13	1e-1	1	1.236e	9.42e2	9.4	8.144
0.932	1e-2	1.48e3	9.4	2.47e1	1	1.236e3	9.42e2	9.4	8.133
0.930	1e-2	3500	2.12	7.03	1	1500	1.03e2	3000	9.656
0.928	9.4	3500	9.4	7.03	1	1500	1.03e2	9.4	8.376
0.926	9.4	1.82e3	9.4	1.29e1	2.22	1e1	9.65e2	9.4	8.461
0.924	9.4	1.82e3	9.4	10	1	1.17e3	9.35e2	1.83e2	8.555
0.922	8.67	9.4	2.87	1e-1	1	100	9.88e2	9.65e1	9.272
0.920	9.4	9.4	9.4	10	1	1500	1.13e3	9.4	7.697
0.918	9.4	2.4	1e-4	10	1	1500	9.36e2	9.4	8.553
0.916	9.4	3500	9.4	10	1	1500	4.32e1	9.4	8.533
0.914	7.24	3500	9.4	1e-1	1	100	4.32e1	9.36e2	7.371
0.912	9.4	2230	9.4	1e-1	1	100	4.32e1	9.36e2	8.122
0.910	9.4	2230	9.4	10	1	1.28e3	4.32e1	3000	8.721
0.908	9.4	2230	9.4	10	1.571	1.28e3	100	3000	8.227
0.906	9.4	2.4	9.4	10	1.571	100	100	3000	6.005
0.904	9.4	1.04e3	9.4	1.58e1	1	100	100	1.75e2	6.781
0.902	9.4	1.04e3	1e-3	1.58e1	1	100	7.06e1	1.75e2	0.564
0.900	1e-2	3500	1e-3	10	1	7.47e2	7.06e1	3.26e1	6.408
0.898	9.4	3500	1e-3	10	1	7.47e2	10	3000	6.932
0.896	9.4	1.05e3	9.4	10	1	100	10	9.4	7.001
0.894	9.4	1.05e3	1e-3	10	1	100	10	2.23e1	4.824
0.892	7.02	3500	1e-3	2.94	1	6.761e2	7.13e2	9.4	7.025
0.890	9.4	3500	1e-3	10	1	7.132e2	7.305e2	9.4	9.172
0.888	1e-2	9.4	9.4	1e-1	1	100	100	9.4	6.071
0.886	9.4	3500	9.4	1e-1	1	100	100	9.4	0.251
0.884	9.4	9.4	9.4	10	2.19	100	7.47e2	3.26e2	2.451
0.882	9.4	5.45e2	1e-3	10	1	100	7.30e2	3000	9.452
0.880	1e-1	3500	9.4	1.59	1	100	100	3000	8.434
0.878	10	3500	1e-3	10	1	100	7.13e2	3000	9.556